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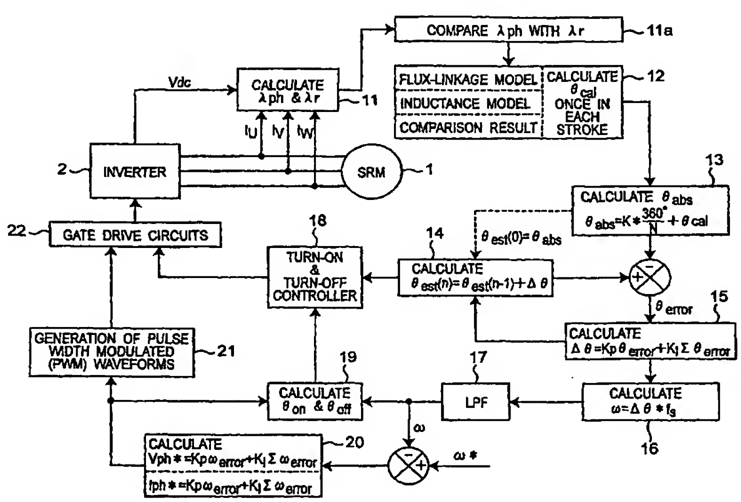
(54) Title: METHOD AND APPARATUS FOR ESTIMATING ROTOR POSITION AND FOR SENSORLESS CONTROL OF A SWITCHED RELUCTANCE MOTOR



(57) Abstract: A discrete rotor position estimation method for a synchronized reluctance motor is provided. A d.c.-link voltage V_{dc} and a phase current I_{ph} are sensed. A flux-linkage λ_{ph} of an active phase is calculated from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph}. The calculated flux-linkage λ_{ph} is compared with a reference flux-linkage λ_r. The reference flux-linkage λ_r corresponds to a reference angle θ_r which lies between angles corresponding to aligned rotor position and non-aligned rotor position in the synchronized reluctance motor. An estimated rotor position θ_{cal} is obtained only once when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r.

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DESCRIPTION

METHOD AND APPARATUS FOR ESTIMATING ROTOR POSITION AND FOR SENSORLESS CONTROL OF A SWITCHED RELUCTANCE MOTOR

Technical field

The present invention relates to the development of closed loop control techniques for switched reluctance motors (SRMs) without a shaft position sensor.

Background art

A switched reluctance motor (SRM) is energized phase by phase in sequence to generate reluctance torque and enable smooth motor rotation. A schematic diagram of a three phase switched reluctance motor is shown in Fig. 1. The number of strokes (N) in SRM per one mechanical revolution is dependent on the number of phases (M) and the number of rotor poles (P) and is given by,

$$N = M*P \quad (1).$$

Therefore, the stroke angle(S) in mechanical degrees is defined as,

$$S = 360° / N \quad (2).$$

When the number of poles is very large and the stroke angle is very small, the SRM is typically operated in open loop as a variable reluctance stepper motor and needs no knowledge of rotor position information during running condition. On the other hand, when the number of poles is small and the stroke angle is very large, the SRM is generally operated in closed loop during running

condition and hence, the knowledge of accurate rotor position information is very important to rotate the motor.

Accurate rotor position information is typically obtained from a shaft position sensor. Shaft position sensors are expensive and have reliability problems and hence, the sensorless operation of SRM is desired.

In a typical position sensorless operation of SRM, rotor position estimation is carried out either discretely i.e. once per stroke angle or continuously. Discrete rotor position estimation is ideal for applications where slow speed response is required where as, continuous rotor position estimation is carried out in applications where fast speed response is desired. Rotor position estimation of the SRM can be carried out from the pre-determined knowledge of its non-linear per phase flux-linkage/current characteristics or the inductance/current characteristics as shown in Fig. 2 and Fig. 3 respectively. Several non-linear analytical models based on the flux-linkage and the inductance characteristics of the motor with respect to the rotor position have been proposed [S.Saha, K.Ochiai, T.Kosaka, N.Matsui and Y.Takeda "Developing a sensorless approach for switched reluctance motors from a new analytical model", 1999 IEEE-IAS Annual meeting, Vol. 1, pp 525-532., and G.Suresh, B.Fahimi, K.M.Rahaman and M.Eshani "Inductance based position encoding for sensorless SRM drives", 1999 IEEE-PESC Annual Meeting, pp 832-837.] to calculate the exact rotor position after sensing the d.c. link voltage V_{dc} and the phase current I_{ph} of the inverter drive circuit as shown in Fig. 4. A voltage sensor VS is used to sense the d.c. link voltage and three current

sensors CS are used to sense the current flowing in each phase winding 1u, 1v or 1w of the SRM 1. The traditional lock and forced drive method with open loop operation can be applied for the starting of these motors at no load. Rotor position estimation scheme is enabled at a minimum speed (ω_{min}) which is normally 10% of the rated speed or higher. The motor moves from open loop to closed loop operation after the rotor position estimation scheme is enabled and then subsequently load is applied to the motor. The entire closed loop control scheme with the rotor position estimation is implemented with the help of a micro-controller or a digital-signal processor.

Disclosure of invention

In a first aspect of the invention, provided is a discrete rotor position estimation method for a synchronized reluctance motor. According to this estimation method, d.c.-link voltage V_{dc} and a phase current I_{ph} are sensed. A flux-linkage λ_{ph} of an active phase is calculated from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph}. The calculated flux-linkage λ_{ph} is compared with a reference flux-linkage λ_r. The reference flux-linkage λ_r corresponds to a reference angle θ_r which lies between angles corresponding to aligned rotor position and non-aligned rotor position in the synchronized reluctance motor. An estimated rotor position θ_{cal} is obtained only once based on the comparison result when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r. From the estimated rotor position θ_{cal}, incremental rotor angle $\Delta\theta$ for every PWM

interrupt is calculated. The knowledge of $\Delta\theta$ is finally used to control the motor.

In a second aspect of the invention, provided is a discrete rotor position estimation method for a synchronized reluctance motor. According to the method in the second aspect, a d.c.-link voltage V_{dc} and a phase current I_{ph} are sensed. A flux-linkage λ_{ph} of an active phase is calculated from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph}. The calculated flux-linkage λ_{ph} is compared with either two or three reference flux-linkages such as λ_{r1},.... The reference flux-linkages λ_{r1},... correspond to a reference rotor angles θ_{r1},... all of them lying between angles corresponding to aligned rotor position and non-aligned rotor position in the synchronized reluctance motor. Rotor positions θ_{cal1},... are obtained based on the comparison results, twice or thrice when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_{r1},.... From the estimated rotor positions θ_{cal1},... incremental rotor angles for every PWM interrupt are also calculated twice or thrice such as $\Delta\theta_1$,.... The values of the incremental rotor angles are averaged to obtain the final incremental rotor angle $\Delta\theta$. The knowledge of the final incremental rotor angle $\Delta\theta$ is used to control the motor.

In the first aspect, the value of the estimated rotor position θ_{cal} obtained from comparison result typically equals the reference rotor angle θ_r. However, the estimated rotor position θ_{cal} may be further modified with an incremental angle ϕ corresponding to the reference rotor angle θ_r to obtain a more accurate estimated rotor

position. This idea can also be extended to the second aspect.

In a third aspect of the invention, provided is a discrete rotor position estimation method for a synchronized reluctance motor. According to the method, a d.c.-link voltage V_{dc} and a phase current I_{ph} are sensed. A flux-linkage λ_{ph} of an active phase is calculated from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph}. The calculated flux-linkage λ_{ph} is compared with a reference flux-linkage λ_r. The reference flux-linkage λ_r corresponds to a reference angle θ_r which lies between angles corresponding to aligned rotor position and non-aligned rotor position of the synchronized reluctance motor. An estimated rotor position θ_{cal} is calculated from the calculated flux-linkage λ_{ph} using either one of the inductance model or the flux linkage model of the active phase, only once when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r. In this case, the ideal instant to estimate the rotor position may be at one PWM interrupt before the next phase is turned ON. From the estimated rotor position θ_{cal}, incremental rotor angle $\Delta\theta$ for every PWM interrupt is calculated. The knowledge of $\Delta\theta$ is finally used to control the motor.

The above idea can be also extended to estimate the rotor position either twice or thrice such as $\theta_{cal1}, \ldots$ from the calculated flux-linkage λ_{ph} using either one of the inductance model or the flux linkage model of the active phase, at every consecutive PWM interrupt when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r. From the estimated rotor positions $\theta_{cal1}, \ldots$

incremental rotor angles for every PWM interrupt are also calculated twice or thrice such as $\Delta\theta_1$,.... The values of the incremental rotor angles are averaged to obtain the final incremental rotor angle $\Delta\theta$. The knowledge of the final incremental rotor angle $\Delta\theta$ is used to control the motor.

In a fourth aspect of the invention, provided is a discrete rotor position estimation method for a synchronized reluctance motor. According to the method, a phase inductance of the synchronized reluctance motor is detected. A minimum region of the phase inductance during turn-on of an active phase is identified. An approximate rotor position θ_{app} is determined from the identified minimum inductance region. From the approximate rotor position θ_{app}, incremental rotor angle $\Delta\theta$ for every PWM interrupt is calculated. The knowledge of $\Delta\theta$ is finally used to control the motor.

In a fifth aspect of the invention, provided is a control method of a synchronized reluctance motor and a technique to obtain the incremental rotor angle $\Delta\theta$ for every PWM interrupt. According to the control method, the estimated rotor position θ_{cal} is obtained by the previously described estimation methods. An absolute rotor position θ_{abs} is calculated from the estimated rotor position θ_{cal} by adding a stroke angle of the motor. The incremental rotor angle $\Delta\theta$ is determined by processing an error between the absolute rotor position θ_{abs} and a finally estimated rotor position θ_{est} through either one of a proportional-integral (PI) control and a proportional control. The finally estimated rotor position θ_{est} in every predetermined period

is generated by adding the incremental rotor angle $\Delta\theta$ to the finally estimated rotor position θ_{est} in the previous cycle. Turn-on and turn-off angles of each phase is controlled based on the finally estimated rotor position θ_{est}.

In a sixth aspect of the invention, provided is a control method of a synchronized reluctance motor and a technique to obtain the incremental rotor angle $\Delta\theta$ for every PWM interrupt. According to the control method, an incremental rotor angle $\Delta\theta$ is calculated by counting the number of PWM interrupts between two consecutive instants when the estimated rotor position θ_{cal} is obtained by the estimation method according to the invention. Delays to turn-off an active phase and turn-on the next phase is generated, in which the delays are normally defined with respect to the reference rotor position θ_r. The delays are adjusted with the estimated rotor position θ_{cal} to turn-off the active phase and turn-on the next phase. A turn-on angle θ_{on} and a turn-off angle θ_{off} of each phase of the motor are controlled based on the adjusted delays decided by the incremental rotor angle $\Delta\theta$.

In the above control methods, a speed ω of the motor may be calculated from the incremental rotor angle $\Delta\theta$ in a relatively slower timer interrupt compared to a PWM interrupt, and a turn-on angle θ_{on} and a turn-off angle θ_{off} of each phase of the motor may be varied continuously based on the speed ω and the torque demand of the motor.

In a seventh aspect of the invention, provided is a control method of a synchronized reluctance motor. According to the control method, a peak of a phase current

and a negative change rate of phase current in each phase are continuously monitored. Turn-off angle is kept fixed and turn-on angle is advanced so that a pre-determined peak phase current and a negative rate of change of phase current corresponding to the maximum torque are achieved.

In the control method, instead of monitoring the negative rate of change of phase current, a lead angle ϕ between the peak current and the peak flux in each phase may be detected to judge the maximum torque at the rated speed condition.

Brief Description of Drawings

Fig. 1 shows the cross-sectional view of a switched reluctance motor.

Fig. 2 shows the per phase flux-linkage / current characteristics with respect to rotor position of a switched reluctance motor.

Fig. 3 shows the per phase inductance / current characteristics with respect to rotor position of a switched reluctance motor.

Fig. 4 shows a typical inverter circuit for the switched reluctance motor.

Fig. 5 shows the region where the reference rotor position θ_r corresponding to the reference flux-linkage λ_r in rotor position estimation technique I can be defined

Fig. 6 shows the instant at which estimation of the exact rotor position θ_{cal} is carried out for the rotor position estimation technique II.

Fig. 7 shows the instant at which the measured actual phase current I_{ph} and the estimated phase current Is

are compared in the discrete rotor position estimation technique III.

Fig. 8 shows the incremental change of per phase flux-linkage λ_{ph} in every PWM interrupt of the processor in accordance with the first exemplary embodiment.

Fig. 9 shows the block diagram for closed loop control using control strategy I in accordance with the first exemplary embodiment.

Fig. 10 shows the turn-on and the turn-off delay with respect to the reference rotor position θ_r in accordance with the second exemplary embodiment.

Fig. 11 shows the block diagram for closed loop control using control strategy II in accordance with the second exemplary embodiment.

Fig. 12A shows two reference flux linkages corresponding to two reference rotor positions in accordance with the third exemplary embodiment.

Fig. 12B shows three reference flux linkages corresponding to three reference rotor positions in accordance with the third exemplary embodiment.

Fig. 13 shows the block diagram for closed loop control using control strategy I in accordance with the third exemplary embodiment.

Fig. 14 shows the block diagram using the discrete rotor position estimation technique III and the control strategy I.

Fig. 15 shows typical per phase current waveforms and per phase flux waveform at the rated speed and the maximum torque condition in accordance with the fifth exemplary embodiment.

Fig. 16 shows the peak current detector block introduced in the closed loop block diagram using discrete rotor position technique I and control strategy I.

Figs. 17A through 17G show examples of applications using the proposed rotor position estimation schemes and control strategies for the switched reluctance motor.

Best mode for carrying out the Invention

The present invention relates to the closed loop control techniques of switched reluctance motors (SRM) without a shaft position sensor where the discrete rotor position estimation techniques are followed. Three typical discrete rotor estimation techniques I, II and III are described briefly below.

(Discrete Rotor Position Estimation Technique I)

In the discrete rotor position estimation technique I, the per phase flux-linkage at rotor position θ_r as shown in Fig. 5 is chosen as a reference flux-linkage λ_r and is expressed as a function of phase current I_{ph} by a simple polynomial expression such as,

$$\lambda_r = \Sigma A_n I_{ph}^n \quad (3).$$

θ_r is defined as any rotor position near the mid-position between the aligned and the non-aligned rotor position which is shown by the shaded area in Fig. 5. Mathematically θ_r can be expressed as,

$$\theta_r = \theta_m \pm \alpha \quad (4)$$

where, θ_m is the exact middle position between the aligned and the non-aligned rotor position and α is the deviation

angle whose maximum value α_{max} is equal to 30° electrical from the middle position. θ_m and α_{max} are expressed in mechanical degrees as follows,

$$\theta_m = (\theta_a + \theta_n)/2 \qquad (5)$$

and

$$\alpha_{max} = 30°/P \qquad (6).$$

θ_a is defined as the aligned position i.e. when a rotor pole aligns with a stator pole. θ_n is defined as the non-aligned position i.e. when a rotor pole is in between two stator poles as shown in Fig. 1. The value of n in the polynomial equation (3) is dependent on the magnetic design of a particular motor. The reason why the near middle position θ_m is selected as a reference position is that the flux linkage varies with the position θ in a high changing rate in vicinity of the middle position θ_m and thus the position θ with respect to the flux linkage can be easily determined.

Use of fast processors will enable to calculate polynomial expressions easily. The reference flux-linkage value λ_r with respect to phase current I_{ph} is pre-determined off-line by locking the rotor at position θ_r and carrying out standard experiments. During motor rotation, the flux-linkage per phase λ_{ph} is calculated on-line at every PWM interrupt or at every half-cycle PWM interrupt of the processor by sensing the d.c.-link voltage V_{dc} and the phase current I_{ph} of the inverter circuit as shown in Fig. 4. It is given by,

$$\lambda_{ph} = (V_{dc} - I_{ph}*R - V_p)*dt \qquad (7)$$

where R is the phase resistance of the SRM in the high frequency mode and V_p is the voltage drop across the power

devices. An average value of mutual flux (maximum 10% of the maximum per phase flux) should be considered for more accurate calculation of the per phase flux-linkage λ_{ph}. The on-line calculated per phase flux-linkage λ_{ph} is continuously compared with the reference flux-linkage λ_r in the processor. At the instant when λ_{ph} is equal to λ_r, the absolute discrete rotor position θ_{abs} in mechanical degrees is determined or estimated as given below

$$\theta_{abs} = K*360°/N + \theta_{cal} \qquad (8)$$

where, $\theta_{cal} = \theta_r$ and $K = (N-1)$.

From the information of θ_{abs}, closed loop control techniques are generated to rotate the motor.

(Discrete Rotor Position Estimation Technique II)

In the discrete rotor position estimation technique II, similarly the d.c.-link voltage V_{dc} and the phase current I_{ph} are sensed and the flux-linkage per phase λ_{ph} is calculated on-line from equation (7) at every PWM interrupt of the processor. From the knowledge of λ_{ph}, the exact rotor position θ_{cal} is calculated only once either from the flux-linkage model or the inductance model of the active phase when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r. The ideal instant to estimate the rotor position may be at one PWM interrupt before the next phase is turned ON. This is shown in Fig. 6. This concept is ideal when the turn-on angle is advanced at the rated speed for high torque applications. The absolute discrete rotor position θ_{abs} in one mechanical cycle is always calculated from the information of the exact rotor position θ_{cal} and is expressed by equation (8).

From the knowledge of θ_{abs} control techniques are again generated to rotate the motor in closed loop.

(Discrete Rotor Position Estimation Technique III)

The discrete rotor position estimation technique III is very simple and does not involve any exact rotor position estimation θ_{cal} as described in techniques I and II. This scheme includes identifying the minimum inductance region during the turn-on of a new phase so that the turn-on angle always lies in the minimum inductance region. This has been made possible by comparing the measured actual phase current I_{ph} with an estimated phase current I_s after a finite time interval t_0 from the turn-on of a new phase as shown in Fig. 7. The estimated current I_s is given by,

$$I_s = (V_{dc} - I_{ph} R - V_p) * t_0 / L_{min} \quad (9).$$

The value of minimum inductance L_{min} is constant for a particular motor and does not vary with the phase current I_{ph} as shown in Fig. 3. The minimum inductance region normally extends to few degrees and is typically dependent on the magnetic design of the motor. Hence, the approximate rotor position θ_{app} is known when the minimum inductance region is identified. Therefore, instead of exact rotor position θ_{cal}, the knowledge of approximate rotor position θ_{app} is used to calculate the absolute discrete rotor position θ_{abs} and rotate the motor in closed loop.

In the discrete rotor position estimation techniques of I, II and III, a rotor position estimation error less than one mechanical degree is difficult to

achieve. A small error in rotor position estimation at a particular speed can decrease the motoring torque i.e. the motor performance to a large extent. Hence, optimum control techniques are invented to minimize rotor position estimation error so that high performance is always achieved for the sensorless drive of SRM's. In addition, control techniques are invented to obtain the high torque even if there is a rotor position estimation error.

(First exemplary embodiment)

In the discrete rotor position estimation technique I, the per phase flux-linkage λ_{ph} is calculated on-line in every PWM interrupt or every PWM half-cycle interrupt by sensing the d.c.-link voltage V_{dc} and the phase current I_{ph} and is defined by the equation (7) above. The incremental change of per phase flux-linkage λ_{ph} at the valley of every PWM interrupt of the processor is shown in Fig. 8 where dt is the time interval between two PWM interrupts and θ_{on} is the turn-on angle and θ_{off} is the turn-off angle. Any digital technique cannot exactly define the instant when the per phase flux-linkage λ_{ph} is equal to the reference flux-linkage λ_r. In this embodiment, the processor within a PWM interrupt identifies an instant when the per phase flux-linkage λ_{ph} is greater than λ_r as shown in Fig. 8. Therefore, for more accurate rotor position estimation, θ_{abs} of equation (8) in the discrete rotor position technique I has to be modified. In the simplest technique, the modification of θ_{abs} in equation (8) can be done by adding an angle ϕ such that,

$$\theta_{abs} = K*360o/N + (\theta_r + \phi) \quad (10).$$

The combined angle (θ_r + ϕ) now defines the exact rotor position θ_{cal}. The angle ϕ can be obtained from a pre-determined two dimensional look-up table in which $\Delta\lambda$ and phase current I_{ph} are the variable parameters. $\Delta\lambda$ is defined as the difference between λ_{ph} and λ_r.

Alternatively, by the discrete rotor position estimation technique II, exact rotor position θ_{cal} should be calculated at the instant when the per phase flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r. Exact rotor position estimation can be carried out by analytical methods based on the flux-linkage model or the inductance model of the SRM. The absolute discrete rotor position θ_{abs} in one mechanical cycle is always calculated from the information of the exact rotor position θ_{cal} and is expressed by equation (8). The value of θ_{abs} which is defined in mechanical degrees in equation (8) can also be expressed in electrical degrees by considering the number of rotor poles (P).

Fig. 9A shows an entire block diagram of a driving apparatus of SRM for achieving the closed loop control with control strategy I according to the invention.

The SRM 1 is driven by the inverter 2 which includes switching devices T1 to T6 as shown in Fig. 4. The gate drive circuit 22 generates pulse width modulated base drive signals to turn-on and turn-off the switching devices T1 to T6 and generate a phase current. PWM control is done by the block 21 with PWM interrupt timer. Turn-on angle θ_{on} and turn-off angle θ_{off} are calculated by the block 19. The turn-on and turn-off controller 18 determines the turn-on and the turn-off timings of each

phase based on the calculated turn-on and turn-off angles θ_{on} and θ_{off} and the estimated rotor position θ_{est}.

In the control strategy I involving the discrete rotor position estimation technique I, phase current I_{ph} and d.c.-link voltage V_{dc} are sensed to calculate the per phase flux-linkage λ_{ph} (by block 11). The flux-linkage λ_{ph} is compared with the reference flux-linkage λ_r (by block 11a). Referring to the comparison result, when the phase flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r, the rotor position θ_{cal} is once calculated (by block 12). The absolute discrete rotor position θ_{abs} is calculated (by block 13) and continuous rotor position θ_{est} is estimated from the absolute discrete rotor position θ_{abs} in the following way (by block 14). At the instant when the exact rotor position θ_{cal} is calculated (by block 12), the error between the absolute rotor position θ_{abs} and the estimated rotor position θ_{est} is calculated and processed in a proportional-integral (PI) control method (by block 15) to give the incremental rotor angle $\Delta\theta$ in every PWM interrupt. $\Delta\theta$ is expressed as

$$\Delta\theta = Kp*\theta_{err} + \Sigma\ KI*\theta_{err} \quad (11)$$

where, $\theta_{err} = (\theta_{abs} - \theta_{est})$. At the start of rotor position estimation, θ_{est} is initialized as θ_{abs} and then calculated as follows

$$\theta_{est}(n) = \theta_{est}(n-1) + \Delta\theta \quad (12).$$

Instead of a proportional-integral control method, a proportional control method can also be used.

The turn-on angle θ_{on} and turn-off angle θ_{off} of each phase is controlled by θ_{est} which can be expressed either in mechanical or electrical degrees (by block 18).

For achieving the turn-on and the turn-off of each phase at any point in between two PWM interrupts, a very fast timer interrupt compared to the PWM interrupt has been defined.

The speed (ω) of the motor is calculated (by block 16) from the incremental rotor angle $\Delta\theta$ in a relatively slow timer interrupt compared to the PWM interrupt. It is given by,

$$\omega = \Delta\theta * fs \quad (13)$$

where, fs is the PWM carrier frequency. The speed ripple is filtered by processing it through a low-pass filter (LPF) 17. If the per phase flux-linkage λ_{ph} is calculated in every half-cycle PWM interrupt, the incremental rotor displacement $\Delta\theta$ has to be defined for every half-cycle PWM interrupt and the speed (ω) of the motor is expressed as,

$$\omega = 2 * \Delta\theta * fs \quad (14).$$

The turn-on and the turn-off angle together with the phase voltage reference (V_{ph}*) or phase current reference (I_{ph}*) are continuously calculated within the processor and are varied depending on the speed (ω) and the torque demand of the motor (by blocks 18-20). In closed loop control, the difference between the commanded speed (ω*) and the calculated speed (ω) is processed through a proportional-integral (PI) control block 20 to generate either the phase voltage reference (V_{ph}*) or the phase current reference (I_{ph}*). Either the phase voltage reference (V_{ph}*) is compared with the PWM carrier waveform or the phase current reference (I_{ph}*) is compared with the original phase current I_{ph} to finally generate the pulse-width modulated (PWM) base drive waveforms (by block 21).

A gate drive circuit 22 controls an inverter 2 using the pulse-width modulated (PWM) waveforms and turn-on and turn-off angles from the turn-on and turn-off controller 18 to drive the SRM 1.

(Second exemplary embodiment)

Fig. 11 shows an entire block diagram of a driving apparatus of SRM for achieving the closed loop control with a control strategy II according to the invention.

In the control strategy II involving the discrete rotor position estimation technique I, instead of calculating θ_{est} continuously to control the turn-on and turn-off angle the incremental rotor displacement $\Delta\theta$ in every PWM interrupt can be calculated in an alternative way which can generate appropriate delays to turn-off the active phase and turn-on the next phase. The speed (ω) of the motor is also calculated from the incremental rotor angle $\Delta\theta$ (by block 16), and the closed loop control can be executed in the similar manner described in the first exemplary embodiment. In the control strategy II, $\Delta\theta$ can be calculated by counting the number of PWM interrupts between two consecutive instants when the per phase flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r (by blocks 13a and 15a), that is, between the instants of $\theta_{cal}(n)$ and $\theta_{cal}(n-1)$. It is given by,

$$\Delta\theta = \text{stroke angle(S)/number of PWM interrupts} \quad (15).$$

In equation (15), $\Delta\theta$ is expressed in mechanical degrees but also can be expressed in electrical degrees by considering the number of rotor poles. The exact rotor

position θ_{cal} at the instant when the per phase flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r is calculated in a similar way as described in the first exemplary embodiment. Calculation of θ_{cal} helps to adjust the turn-on and the turn-off delay and this is explained as follows. The turn-off delay (x°) of the active phase and the turn-on delay (y°) of the next phase are always defined with respect to the reference rotor position θ_r as shown in Fig. 10 for a specific speed (ω) of the motor (by block 18b). The difference ϕ between the exact rotor position θ_{cal} and the reference rotor position θ_r is always estimated so that the turn-off delay (x°) of the active phase and the turn-on delay (y°) of the next phase are modified as $X_1°$ and $Y_1°$, respectively (by block 18a). The modified turn-off delay ($X_1°$) and the turn-on delay ($Y_1°$) are now redefined with respect to the exact rotor position θ_{cal}, and can be expressed as,

$$X_1° = x° - \phi \quad (16) \text{ and}$$

$$Y_1° = y° - \phi \quad (17).$$

For achieving the turn-on and the turn-off of each phase at any point in between two PWM interrupts, a very fast timer interrupt compared to the PWM interrupt has been defined as explained in the first exemplary embodiment. In addition, if the per phase flux-linkage λ_{ph} is calculated in every half-cycle PWM interrupt, the incremental rotor displacement $\Delta\theta$ has to be defined for every half-cycle PWM interrupt.

The above control technique will help to achieve both high performance as well as maximum torque of the motor at the rated speed.

(Third exemplary embodiment)

The discrete rotor position estimation technique I described in the first and the second exemplary embodiment includes comparing the per phase flux-linkage λ_{ph} with only one reference flux-linkage λ_r defined for a rotor position θ_r. Hence, in both cases, exact rotor position θ_{cal} and incremental rotor angle $\Delta\theta$ are calculated only once at the instant when the per phase flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r during the conduction of each active phase. The discrete rotor position estimation technique I can be extended by defining two reference flux-linkages λ_{r1} and λ_{r2} at rotor positions θ_{r1} and θ_{r2} respectively as shown in Fig. 12A or three reference flux-linkages λ_{r1}, λ_{r2} and λ_{r3} at rotor positions θ_{r1}, θ_{r2} and θ_{r3} respectively as shown in Fig.12B by polynomial expression in phase current I_{ph}. All these rotor positions lie near the mid-position θm with a deviation angle α_{max} of 30°. Hence, the on-line estimated per phase flux-linkage λ_{ph} is compared with two or three reference flux-linkages and accordingly two exact rotor positions (θ_{cal1} and θ_{cal2}) or three exact rotor positions (θ_{cal1}, θ_{cal2} and θ_{cal3}) are calculated during the active conduction of each phase based on the comparison result.

Alternatively, the discrete rotor position estimation technique II can be extended by calculating the exact rotor positions either twice (θ_{cal1} and θ_{cal2}) or thrice (θ_{cal1}, θ_{cal2} and θ_{cal3}) from the calculated flux-linkage λ_{ph} by using either one of the inductance model or the flux linkage model of the active phase, at every

consecutive PWM interrupt when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r corresponding to reference rotor angle θ_r.

Now from $\theta_{cal1}, \ldots$ by following either the control strategy I or the control strategy II, incremental rotor angle for every PWM interrupt is also calculated twice ($\Delta\theta_1$ and $\Delta\theta_2$) or thrice ($\Delta\theta_1$, $\Delta\theta_2$ and $\Delta\theta_3$) during the active conduction of each phase. The final incremental rotor angle $\Delta\theta$ for every PWM interrupt is the average of all the calculated incremental rotor angle. The final incremental rotor angle $\Delta\theta$ is used for the estimation of rotor position θ_{est} in control strategy I or providing the necessary delay for the turn-on or the turn-off a phase as described in control strategy II. The speed (ω) of the motor is also calculated from the final incremental rotor angle $\Delta\theta$. A control block diagram using the control strategy I and calculating the incremental rotor angle for every PWM interrupt twice is shown in Fig. 13. In this figure, absolute discrete rotor positions θ_{abs1} and θ_{abs2} are calculated, respectively (by blocks 13a and 13b). Then the incremental rotor angles ($\Delta\theta_1$ and $\Delta\theta_2$) are calculated respectively and averaged to obtain $\Delta\theta$ (by blocks 15a to 15c). A control block diagram for calculating the incremental rotor angle thrice can be similarly obtained.

(Fourth exemplary embodiment)

In the discrete rotor position estimation technique II, the d.c-link voltage V_{dc} and the phase current I_{ph} are sensed and the flux-linkage per phase λ_{ph} is calculated on-line from equation (7) at every PWM

interrupt of the processor. From the knowledge of λ_{ph}, the exact rotor position θ_{cal} is calculated either from the flux-linkage model or the inductance model of the active phase at one PWM interrupt before the next phase is turned ON. This is shown in Fig.6. This concept is ideal when the turn-on angle is advanced at the rated speed for high torque applications. The absolute discrete rotor position θ_{abs} in one mechanical cycle is always calculated from the information of the exact rotor position θ_{cal} and is expressed by equation (7).

From the knowledge of θ_{abs}, control strategies I and II are again applied in the discrete rotor position estimation technique II to rotate the motor in closed loop.

(Fifth exemplary embodiment)

There exist many industrial applications which require motor operation only at the rated speed and the maximum torque condition instead of the continuous variable speed-torque operation. For such applications, the discrete rotor position estimation technique III is proposed.

Fig. 14 shows an entire block diagram of driving apparatus of SRM using the discrete rotor position estimation technique III and the control strategy I. It should be noted that identical block diagram can be drawn for the discrete rotor position estimation technique III and the control strategy II.

The discrete rotor position technique III is very simple and does not involve any exact rotor position estimation θ_{cal} from the flux-linkage model or the

inductance model as described in techniques I and II. The discrete rotor position technique III includes identifying the minimum inductance region during the turn-on of a new phase so that the turn-on angle always lies in the minimum inductance region. This has been made possible by comparing the measured actual phase current I_{ph} with the estimated phase current I_s after a finite time interval t_0 from the turn-on of a new phase as shown in Fig. 7. The estimated current I_s is calculated from equation (9) in the block 11a.

The locking of a particular phase and open loop starting technique with a forced drive always ensures that the turn-on angle is initially synchronized with the minimum inductance region. Coinciding the turn-on angle always with the minimum inductance region also guarantees perfect synchronous operation of the motor. Initially the turn-on angle can be anywhere between θ_1 and θ_2 as shown in Fig. 7. However, the turn-on angle is initialized with θ_0 which is the middle position between θ_1 and θ_2. Therefore, the approximate rotor position θ_{app} at t_0 can be easily calculated. In this embodiment, instead of exact rotor position θ_{cal}, approximate rotor position θ_{app} is obtained (in block 12a), and the knowledge of approximate rotor position θ_{app} is used to calculate the absolute discrete rotor position θ_{abs} (in block 13b) and rotate the motor in closed loop by applying either control strategy I or II.

(Sixth exemplary embodiment)

In the discrete rotor position estimation

techniques of I, II and III, a rotor position estimation error less than one mechanical degree is difficult to achieve. At the rated speed and the maximum torque condition, the SRM operates in the single pulse mode. Typical per phase current waveforms with a variable turn-on angle and a fixed turn-off angle at the rated speed are shown in Fig. 15. The per phase flux waveform corresponding to the rated speed and the maximum torque condition is also shown in Fig. 15. From Fig. 15 it can be easily understood that the peak phase current (I_{ph}(peak)) which is immediately followed by the negative rate of change of phase current has to be continuously monitored if a specific application requires maximum torque operation at the rated speed. Therefore, keeping the turn-off angle fixed, the turn-on angle is advanced until the pre-determined reference peak phase current (I_p*) and a reference negative rate of change of phase current (dI_{ph}*/dt) corresponding to the maximum torque are achieved. Instead of monitoring the negative rate of change of phase current, the lead angle (ϕ) between the peak current (I_{ph}(peak)) and the peak flux (λ_{ph}(peak)) can be also monitored to judge the maximum torque at the rated speed condition. As shown in Fig. 16, the peak current detector block 30 is introduced in the closed loop block diagram using discrete rotor position technique I and control strategy I.

(Industrial Applicability)

The proposed discrete position sensorless estimation schemes for the switched reluctance motors are

ideal for several automotive applications such as the compressor drive in car air-conditioners for a conventional gasoline vehicle, an electric vehicle and a hybrid electric vehicle.

Examples of applications using the proposed rotor position estimation schemes and control strategies for the switched reluctance motor are shown in Figs. 17A through 17G.

Fig. 17A is an explanatory diagram of an application of the invention to an electric vehicle. The drive unit 100 includes a switched reluctance motor 1, an inverter 2, a current sensor 5, and SRM control system 50. Typically it means that the SRM control system 50 has the same structure as that shown in Fig. 9, 11, 13, 14 or 16 except for the SRM 1. The drive unit 100 is coupled with a main ECU (Electrical Control Unit) 61 and a gear 63.

Fig. 17B also shows an application of the invention to a hybrid electric vehicle. The engine 65 is further provided to the structure of the Fig. 17B. Fig. 17C shows an application of the invention to a water pump.

Fig. 17D shows an application of the invention to a compressor drive of an air conditioner or a refrigerator. The drive unit 100 drives a compressor 70 which compresses refrigerant circulating in a refrigeration cycle 71.

Fig. 17E shows an application of the invention to a machine tool. Fig. 17F shows an application of the invention to a cleaner. Fig. 17G shows an application of the invention to a fan device.

However, the proposed discrete position sensorless estimation techniques can be extended to any

industrial applications involving these types of motors where the speed response required is low.

Although the present invention has been described in connection with specified embodiments thereof, many other modifications, corrections and applications are apparent to those skilled in the art. Therefore, the present invention is not limited by the disclosure provided herein but limited only to the scope of the appended claims.

CLAIMS

1. A discrete rotor position estimation method for a synchronized reluctance motor comprising:

sensing a d.c.-link voltage V_{dc} and a phase current I_{ph};

calculating a flux-linkage λ_{ph} of an active phase from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph};

comparing the calculated flux-linkage λ_{ph} with a reference flux-linkage λ_r, the reference flux-linkage λ_r corresponding to a reference angle θ_r which lies between angles corresponding to aligned rotor position and non-aligned rotor position in the synchronized reluctance motor; and

typically obtaining an estimated rotor position θ_{cal} equal to θ_r only once during the active conduction of a phase based on the comparison result when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r.

2. A discrete rotor position estimation method for a synchronized reluctance motor comprising:

sensing a d.c.-link voltage V_{dc} and a phase current I_{ph};

calculating a flux-linkage λ_{ph} of an active phase from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph};

comparing the calculated flux-linkage λ_{ph} with either two or three reference flux-linkages such as $\lambda_{r1}, \ldots,$

corresponding to reference rotor angles $\theta_{r1},\ldots$ all of them lying between angles corresponding to aligned rotor position and non-aligned rotor position in the synchronized reluctance motor;

typically obtaining rotor positions $\theta_{cal1},\ldots$ equal to $\theta_{r1},\ldots$ based on the comparison results, twice or thrice during the active conduction of a phase when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkages $\lambda_{r1},\ldots$.

3. The discrete rotor position estimation method according to claim 1 or 2, further comprising modifying the estimated rotor position θ_{cal} with an incremental angle ϕ corresponding to the reference angle θ_r to obtain a more accurate estimated rotor position.

4. A discrete rotor position estimation method for a synchronized reluctance motor comprising:

sensing a d.c.-link voltage V_{dc} and a phase current I_{ph};

calculating a flux-linkage λ_{ph} of an active phase from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph};

comparing the calculated flux-linkage λ_{ph} with a reference flux-linkage λ_r, the reference flux-linkage λ_r corresponding to a reference angle θ_r which lies between angles corresponding to aligned rotor position and non-aligned rotor position of the synchronized reluctance motor; and

calculating an estimated rotor position θ_{cal} from

the calculated flux-linkage λ_{ph} using either one of the inductance model or the flux linkage model of the active phase, only once during the active conduction of a phase when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r.

5. The discrete rotor position estimation method according to claim 4, wherein the estimated rotor position is calculated at one PWM interrupt before the next phase is turned ON.

6. A discrete rotor position estimation method for a synchronized reluctance motor comprising:

sensing a d.c.-link voltage V_{dc} and a phase current I_{ph};

calculating a flux-linkage λ_{ph} of an active phase from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph};

comparing the calculated flux-linkage λ_{ph} with a reference flux-linkage λ_r, the reference flux-linkage λ_r corresponding to a reference angle θ_r which lies between angles corresponding to aligned rotor position and non-aligned rotor position of the synchronized reluctance motor; and

calculating estimated rotor positions either twice or thrice during the active conduction of a phase such as $\theta_{cal1}, \ldots$ from the calculated flux-linkage λ_{ph} using either one of the inductance model or the flux linkage model of the active phase, at every consecutive PWM interrupt when the calculated flux-linkage λ_{ph} is greater

than the reference flux-linkage λ_r.

7. The discrete rotor position estimation method according to any one of claims 1 to 6, wherein the reference flux-linkage λ_r at the reference rotor position θ_r is predetermined experimentally and is expressed as a polynomial expression of phase current I_{ph}. The reference rotor position θ_r is typically defined at any region near the mid-position θ_m of the aligned and the non-aligned position with a maximum deviation angle α_{max} of 30° electrical. The reference flux-linkage λ_r involving the polynomial expression in phase current I_{ph} is calculated within a processor.

8. The discrete rotor position estimation method according to claim 1 or 3, wherein the incremental rotor angle $\Delta\theta$ for every PWM interrupt is obtained only once from the knowledge of θ_{cal} during the active conduction of a phase when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r.

9. The discrete rotor position estimation method according to claim 2 or 5, wherein the incremental rotor angles such as $\Delta\theta_1, \ldots$ for every PWM interrupt are obtained either twice or thrice from the knowledge of $\theta_{cal1}, \ldots$ during the active conduction of a phase when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r, and the incremental rotor angles $\Delta\theta_1, \ldots$ are averaged to obtain the final incremental rotor angle $\Delta\theta$.

10. A discrete rotor position estimation method for a synchronized reluctance motor comprising:

detecting a phase inductance of the synchronized reluctance motor;

identifying an minimum region of the phase inductance during turn-on of an active phase;

determining a rotor position θ_{app} from the identified minimum region, as an estimated rotor position θ_{cal} and using it to calculate incremental rotor angle $\Delta\theta$ for every PWM interrupt.

11. A control method of a synchronized reluctance motor comprising:

obtaining the estimated rotor position θ_{cal} by the estimation method according to one of claims 1 to 6 and 9;

calculating an absolute rotor position θ_{abs} from the estimated rotor position θ_{cal} by adding a stroke angle of the motor;

determining the incremental rotor angle $\Delta\theta$ by processing an error between the absolute rotor position θ_{abs} and a finally estimated rotor position θ_{est} through either one of a proportional-integral (PI) control and a proportional control;

generating the finally estimated rotor position θ_{est} in every predetermined period by adding the incremental rotor angle $\Delta\theta$ to the finally estimated rotor position θ_{est} in the previous cycle; and

controlling turn-on and turn-off angles of each

phase based on the finally estimated rotor position θ_{est}.

12. A control method of a synchronized reluctance motor comprising:

calculating an incremental rotor angle $\Delta\theta$ by counting the number of PWM interrupts between two consecutive instants when the estimated rotor position θ_{cal} is obtained by the method according to one of claims 1 to 6 and 9;

generating delays to turn-off an active phase and turn-on the next phase, the delays normally defined with respect to the reference rotor position θ_r;

adjusting the delays with the estimated rotor position θ_{cal} to turn-off the active phase and turn-on the next phase; and

controlling a turn-on angle θ_{on} and a turn-off angle θ_{off} of each phase of the motor based on the incremental rotor angle $\Delta\theta$ and the adjusted delays.

13. The control method according to claim 11 or 12, further comprising

calculating a speed ω of the motor from the incremental rotor angle $\Delta\theta$ in a relatively slower timer interrupt compared to a PWM interrupt, and

varying continuously a turn-on angle θ_{on} and a turn-off angle θ_{off} of each phase of the motor based on the speed ω and the torque demand of the motor.

14. The control method according to claim 11 or 12, further comprising defining a timer interrupt faster than

the PWM interrupt for achieving the turn-on and the turn-off of each phase at any point in between two PWM interrupts.

15. A control method of a synchronized reluctance motor comprising:

monitoring continuously a peak of a phase current and a negative change rate of phase current in each phase; and

keeping the turn-off angle fixed, and advancing the turn-on angle so that a pre-determined peak phase current and a negative rate of change of phase current corresponding to the maximum torque are achieved.

16. The control method according to claim 15, wherein instead of monitoring the negative rate of change of phase current a lead angle ϕ between the peak current and the peak flux in each phase is monitored, to judge the maximum torque at the rated speed condition.

17. An apparatus for estimating discretely a rotor position for a synchronized reluctance motor comprising:

sensor operable to sense a d.c.-link voltage V_{dc} and a phase current I_{ph};

section operable to calculate a flux-linkage λ_{ph} of an active phase from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph};

section operable to calculate the reference flux-linkage λ_r from the polynomial expression in phase current I_{ph};

section operable to compare the calculated flux-linkage λ_{ph} with the reference flux-linkage λ_{r}, the reference flux-linkage λ_{r} corresponding to a reference angle θ_{r} which lies between angles corresponding to aligned rotor position and non-aligned rotor position in the synchronized reluctance motor; and

section operable to obtain an estimated rotor position θ_{cal} only once when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_{r}.

18. An apparatus for estimating discretely a rotor position for a synchronized reluctance motor comprising:

sensor operable to sense a d.c.-link voltage V_{dc} and a phase current I_{ph};

section operable to calculate a flux-linkage λ_{ph} of an active phase from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph};

section operable to calculate reference flux-linkages $\lambda_{r1}, \ldots$ from the polynomial expression in phase current I_{ph};

section operable to compare the calculated flux-linkage λ_{ph} with reference flux-linkages $\lambda_{r1}, \ldots$ the reference flux-linkages $\lambda_{r1}, \ldots$ corresponding respectively to reference angles $\theta_{r1}, \ldots$ which lie between angles corresponding to aligned rotor position and non-aligned rotor position in the synchronized reluctance motor;

section operable to obtain rotor positions $\theta_{cal1}, \ldots$ based on the comparison result, twice or thrice when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkages $\lambda_{r1}, \ldots$.

19. The apparatus according to claim 17 or 18, further comprising section operable to modify the estimated rotor position θ_{cal} with an incremental angle ϕ corresponding to the reference angle θ_r to obtain a more accurate estimated rotor position.

20. An apparatus for estimating discretely a rotor position for a synchronized reluctance motor comprising:

sensor operable to sense a d.c.-link voltage V_{dc} and a phase current I_{ph};

section operable to calculate a flux-linkage λ_{ph} of an active phase from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph};

section operable to calculate the reference flux-linkage λ_r from the polynomial expression in phase current I_{ph};

section operable to compare the calculated flux-linkage λ_{ph} with a reference flux-linkage λ_r, the reference flux-linkage λ_r corresponding to a reference angle θ_r which lies between angles corresponding to aligned rotor position and non-aligned rotor position of the synchronized reluctance motor; and

section operable to calculate an estimated rotor position θ_{cal} from the calculated flux-linkage λ_{ph} using either one of the inductance model or the flux linkage model of the active phase, only once when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r.

21. The apparatus according to claim 20, wherein the estimated rotor position is calculated at one PWM interrupt before the next phase is turned ON.

22. An apparatus for estimating discretely a rotor position for a synchronized reluctance motor comprising:

sensor operable to sense a d.c.-link voltage V_{dc} and a phase current I_{ph};

section operable to calculate a flux-linkage λ_{ph} of an active phase from the sensed d.c.-link voltage V_{dc} and the sensed phase current I_{ph};

section operable to calculate the reference flux-linkage λ_r from the polynomial expression in phase current I_{ph};

section operable to compare the calculated flux-linkage λ_{ph} with two or three reference flux-linkages $\lambda_{r1}, \ldots$ the reference flux-linkages $\lambda_{r1}, \ldots$ respectively corresponding to reference angles $\theta_{r1}, \ldots$ which lie between angles corresponding to aligned rotor position and non-aligned rotor position of the synchronized reluctance motor; and

section operable to calculate estimated rotor positions $\theta_{cal1}, \ldots$ either twice or thricefrom the calculated flux-linkage λ_{ph} using either one of the inductance model or the flux linkage model of the active phase, at every consecutive PWM interrupt when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage $\lambda_{r1}, \ldots$.

23. The apparatus according to claim 17 or 20,

further comprising a section operable to estimate the incremental rotor angle $\Delta\theta$ for every PWM interrupt only once from the knowledge of θ_{cal} during the active conduction of a phase when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage λ_r.

24. The apparatus according to claim 18 or 22, further comprising a section operable to estimate the incremental rotor angles $\Delta\theta_1, \ldots$ for every PWM interrupt either twice or thrice from the knowledge of $\theta_{cal1}, \ldots$ during the active conduction of a phase when the calculated flux-linkage λ_{ph} is greater than the reference flux-linkage $\lambda_{r1}, \ldots$, and a section operable to average the incremental rotor angles $\Delta\theta_1, \ldots$ to obtain the final incremental rotor angle $\Delta\theta$.

25. An apparatus for estimating discretely a rotor position for a synchronized reluctance motor comprising:

section operable to detect a phase inductance of the synchronized reluctance motor;

section operable to identify an minimum region of the phase inductance during turn-on of an active phase;

section operable to determine a rotor position θ_{app} from the identified minimum region, as an estimated rotor position θ_{cal}; and

section operable to obtain the incremental rotor angle $\Delta\theta$ from θ_{app}.

26. An apparatus for controlling a synchronized reluctance motor comprising:

section operable to obtain the estimated rotor position θ_{cal} by the estimation method according to any one of claims 12 to 17;

section operable to calculate an absolute rotor position θ_{abs} from the estimated rotor position θ_{cal} by adding a stroke angle of the motor;

section operable to determine the incremental rotor angle $\Delta\theta$ by processing an error between the absolute rotor position θ_{abs} and a finally estimated rotor position θ_{est} through either one of a proportional-integral (PI) control and a proportional control;

section operable to generate the finally estimated rotor position θ_{est} in every predetermined period by adding the incremental rotor angle $\Delta\theta$ to the finally estimated rotor position θ_{est} in the previous cycle; and

section operable to control turn-on and turn-off angles of each phase based on the finally estimated rotor position θ_{est}.

27. An apparatus for controlling a synchronized reluctance motor comprising:

section operable to calculate an incremental rotor angle $\Delta\theta$ by counting the number of PWM interrupts between two consecutive instants when the estimated rotor position θ_{cal} is obtained by the method according to any one of claims 12 to 17;

section operable to generate delays to turn-off an active phase and turn-on the next phase, the delays normally defined with respect to the reference rotor position θ_r;

section operable to adjust the delays with the estimated rotor position θ_{cal} to turn-off the active phase and turn-on the next phase; and

section operable to control a turn-on angle θ_{on} and a turn-off angle θ_{off} of each phase of the motor based on the adjusted delays decided by the incremental rotor angle $\Delta\theta$.

28. The apparatus according to claim 18 or 19, further comprising

section operable to calculate a speed ω of the motor is calculated from the incremental rotor angle $\Delta\theta$ in a relatively slower timer interrupt compared to a PWM interrupt, and

section operable to vary continuously a turn-on angle θ_{on} and a turn-off angle θ_{off} of each phase of the motor based on the speed ω and the torque demand of the motor.

29. An apparatus for controlling a synchronized reluctance motor comprising:

section operable to monitor continuously a peak of a phase current and a negative change rate of phase current in each phase; and

section operable to keep the turn-off angle fixed, and advance the turn-on angle so that a pre-determined peak phase current and a negative rate of change of phase current corresponding to the maximum torque are achieved.

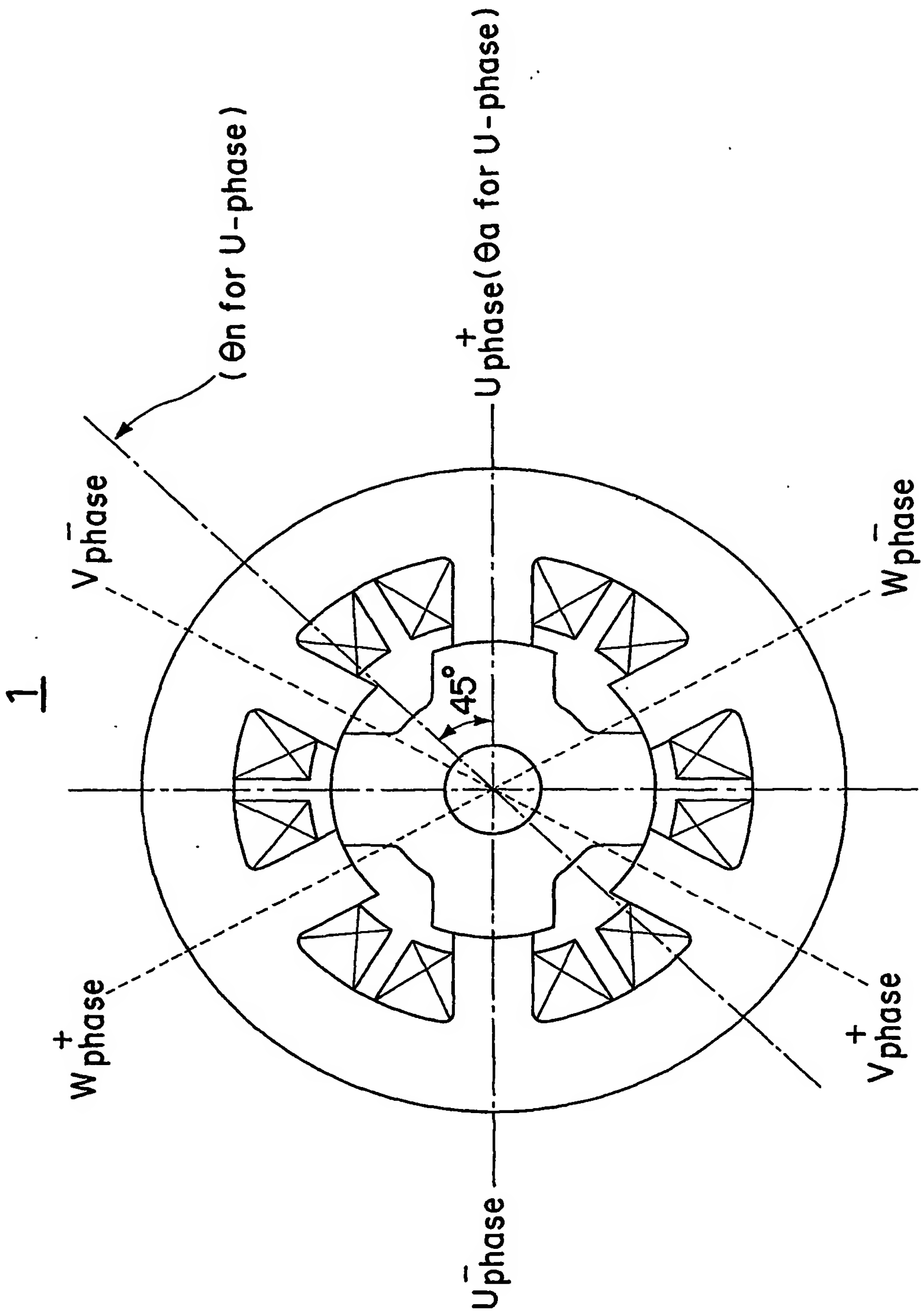
30. The apparatus according to claim 29, wherein

instead of monitoring the negative rate of change of phase current, the section operable to monitor monitors a lead angle ϕ between the peak current and the peak flux in each phase, to judge the maximum torque at the rated speed condition.

31. A motor drive system comprising a synchronized switched reluctance motor to provide a driving power to a compressor drive and driving the synchronized switched reluctance motor by the control method according to any one of claims 11 to 16.

32. An air conditioner comprising the motor drive system according to claim 31.

Fig. 1


1
(θn for U-phase)
U+phase(θa for U-phase)
V-phase
W-phase
45°
W+phase
V+phase
U-phase

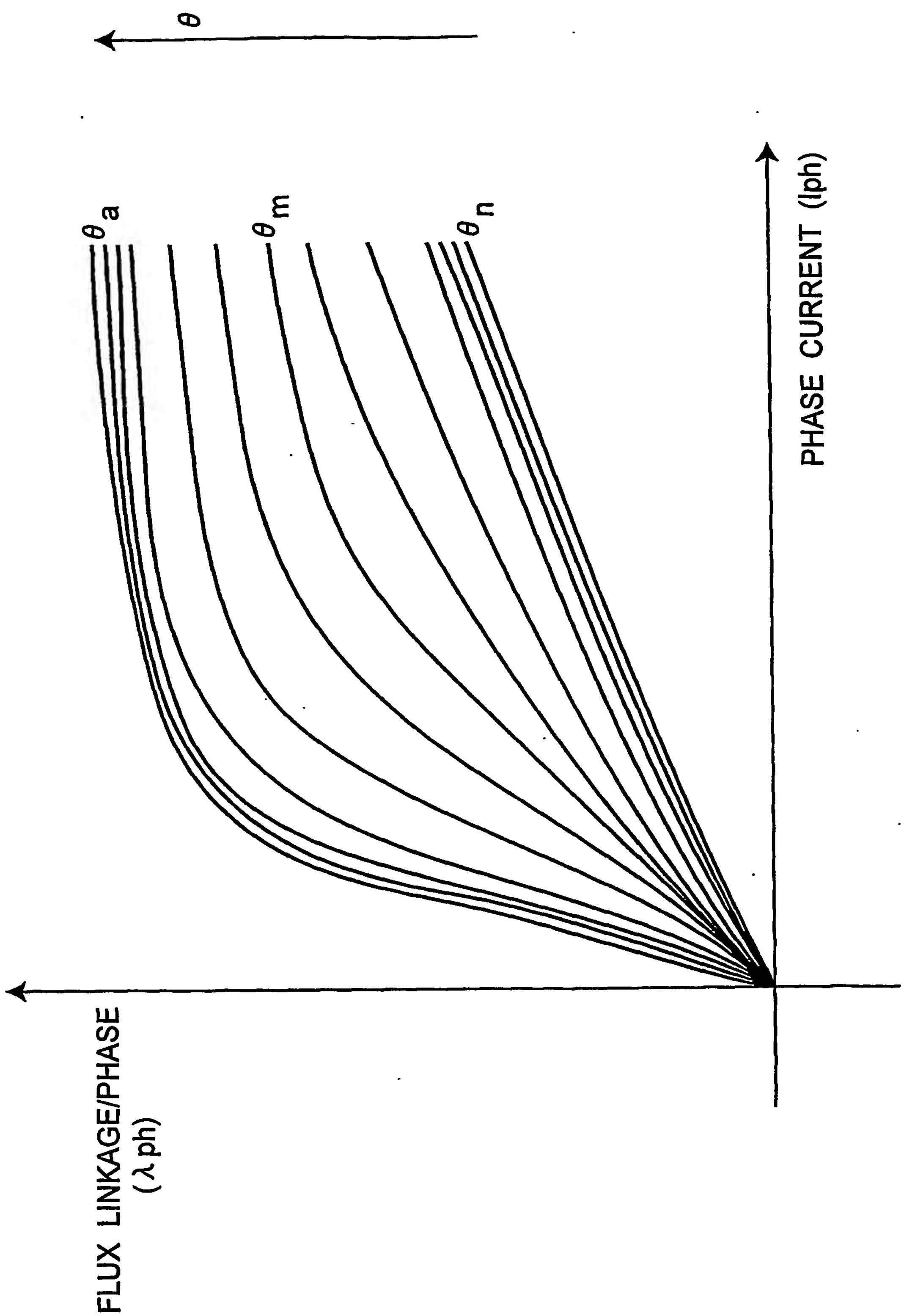


Fig.2

Fig.3

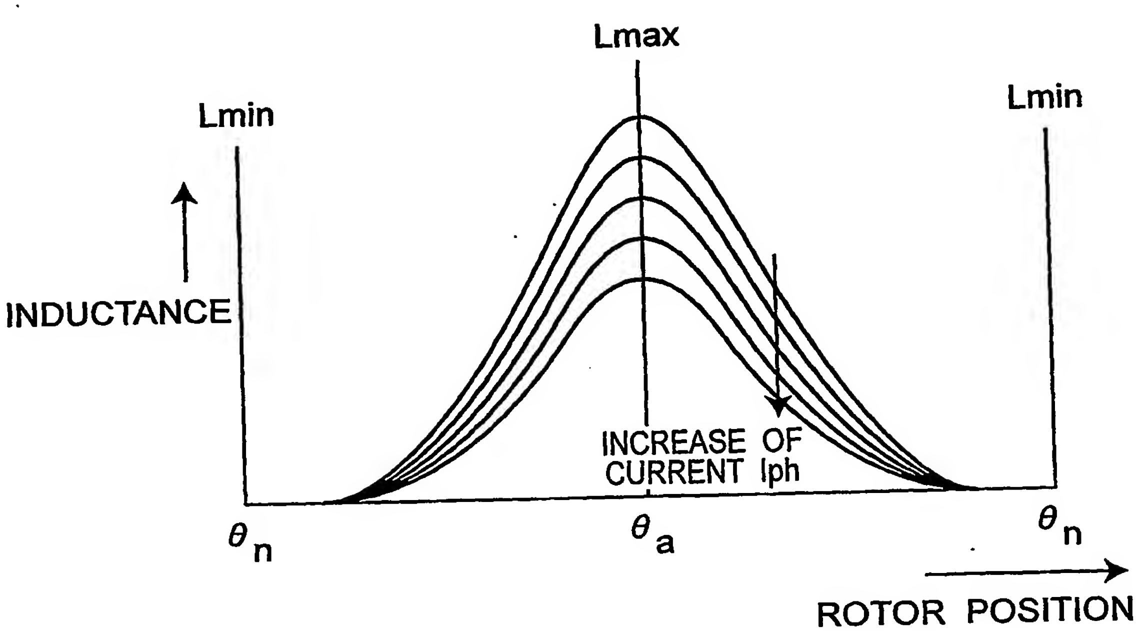

Lmax
Lmin
Lmin
INDUCTANCE
INCREASE OF CURRENT Iph
θ_n
θ_a
θ_n
ROTOR POSITION

Fig.4

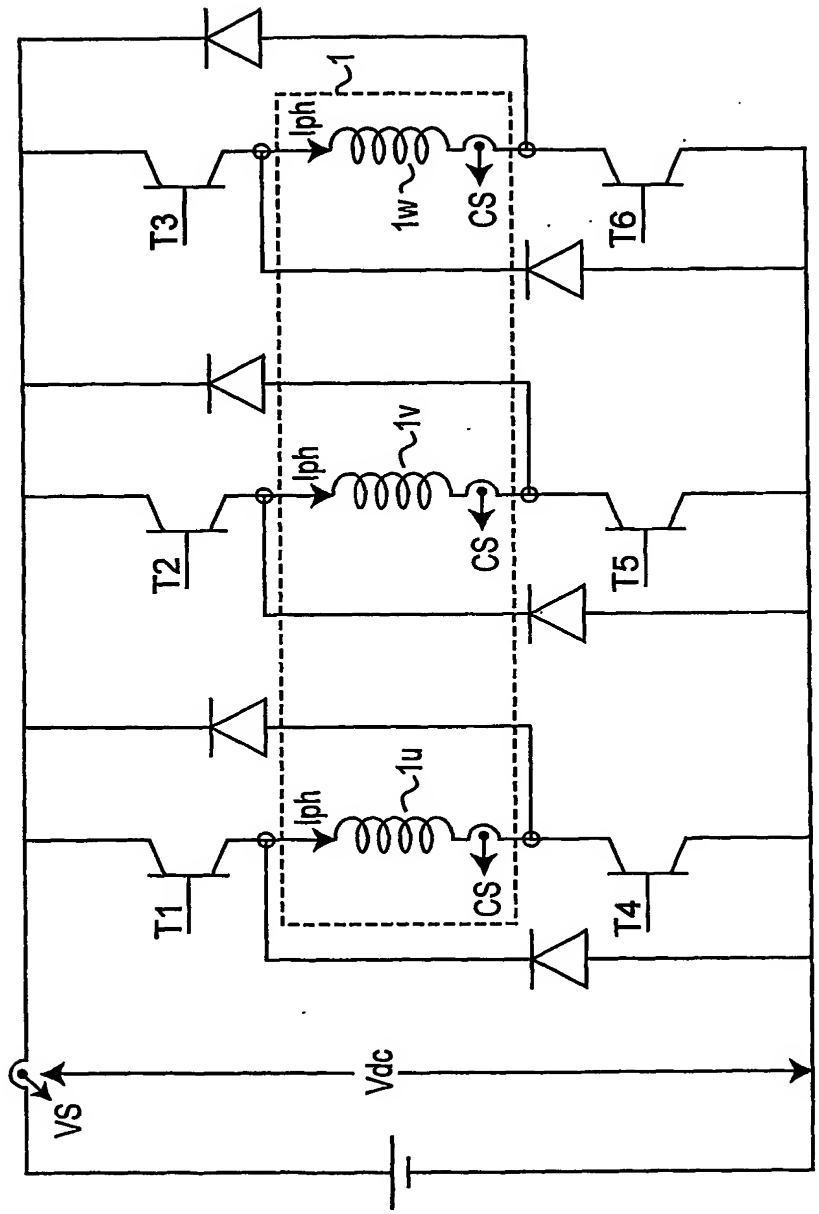
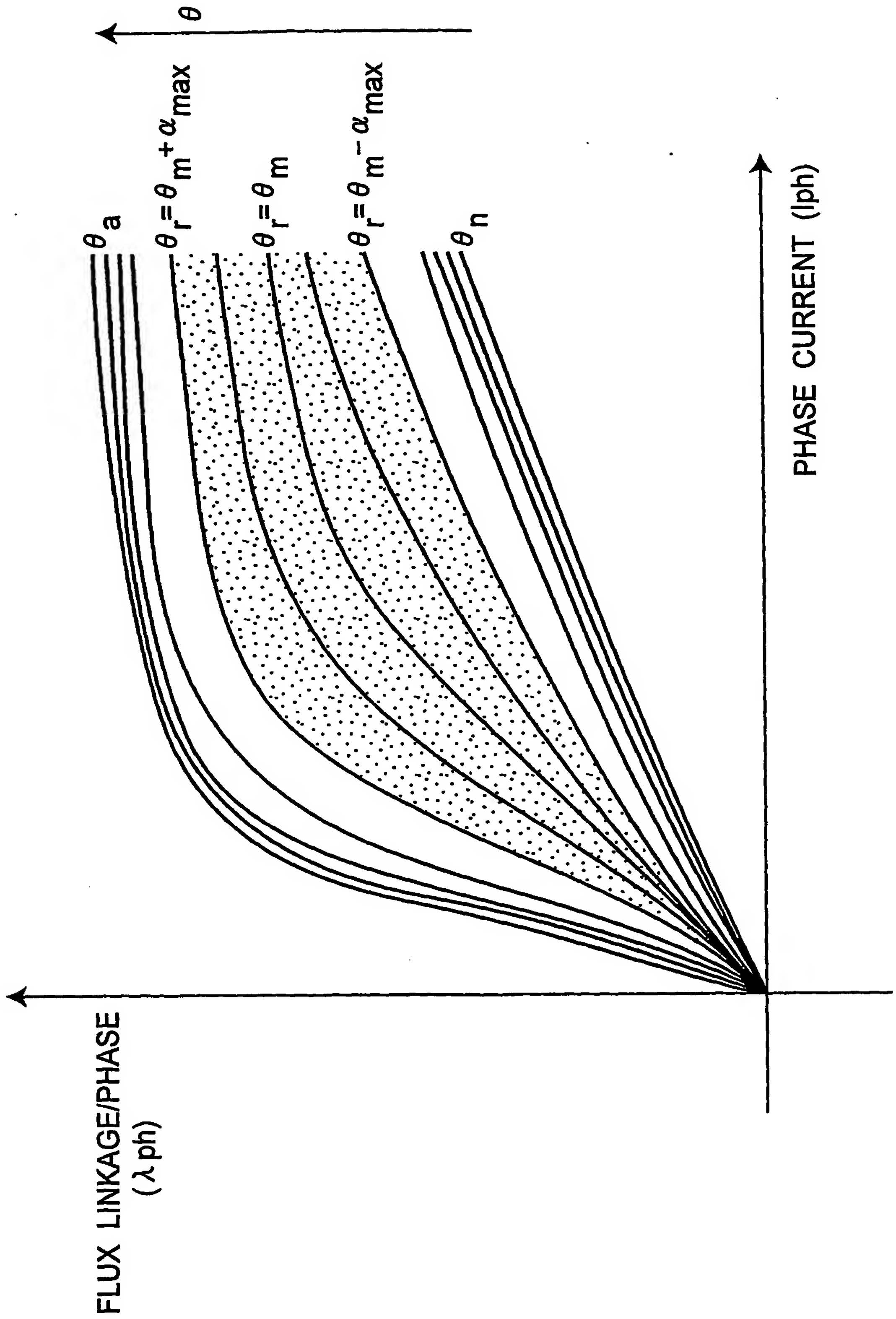
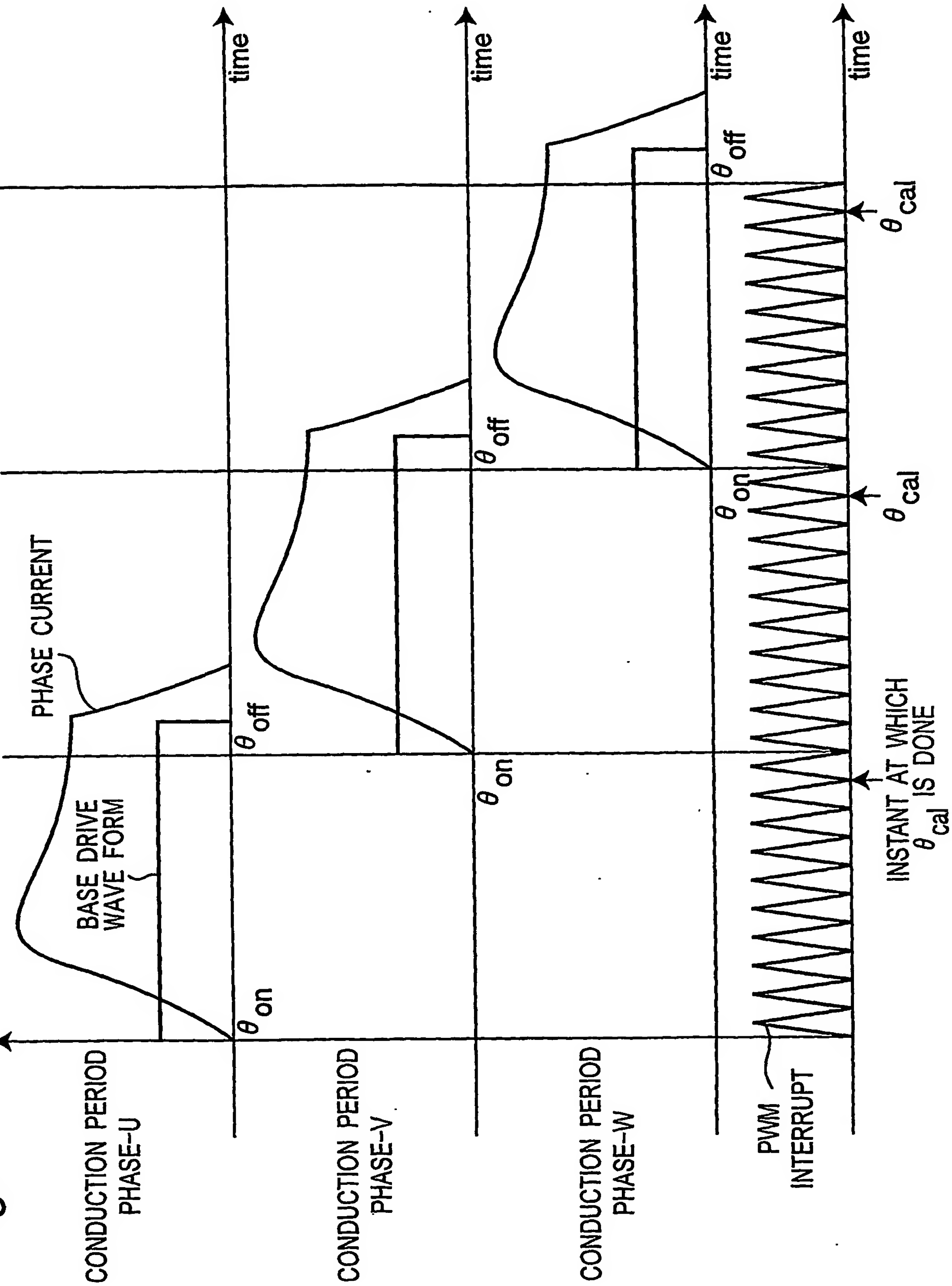


Fig.5



θ
θa
θr=θm+αmax
θr=θm
θr=θm−αmax
θn
PHASE CURRENT (Iph)
FLUX LINKAGE/PHASE
(λph)

Fig.6



CONDUCTION PERIOD PHASE-U
CONDUCTION PERIOD PHASE-V
CONDUCTION PERIOD PHASE-W
PWM INTERRUPT
BASE DRIVE WAVE FORM
PHASE CURRENT
θ_{on}
θ_{off}
θ_{cal}
INSTANT AT WHICH θ_{cal} IS DONE
time

Fig.7

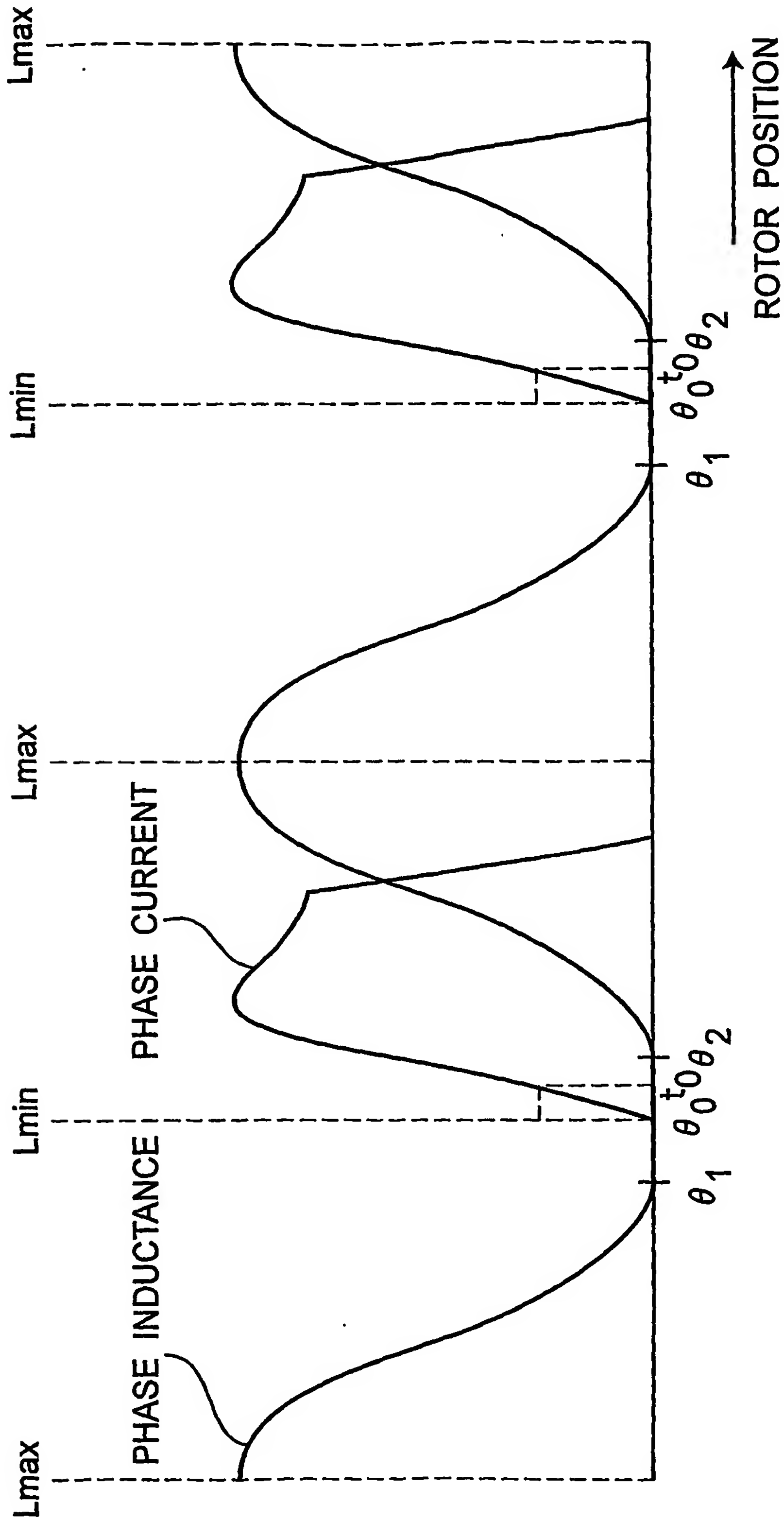
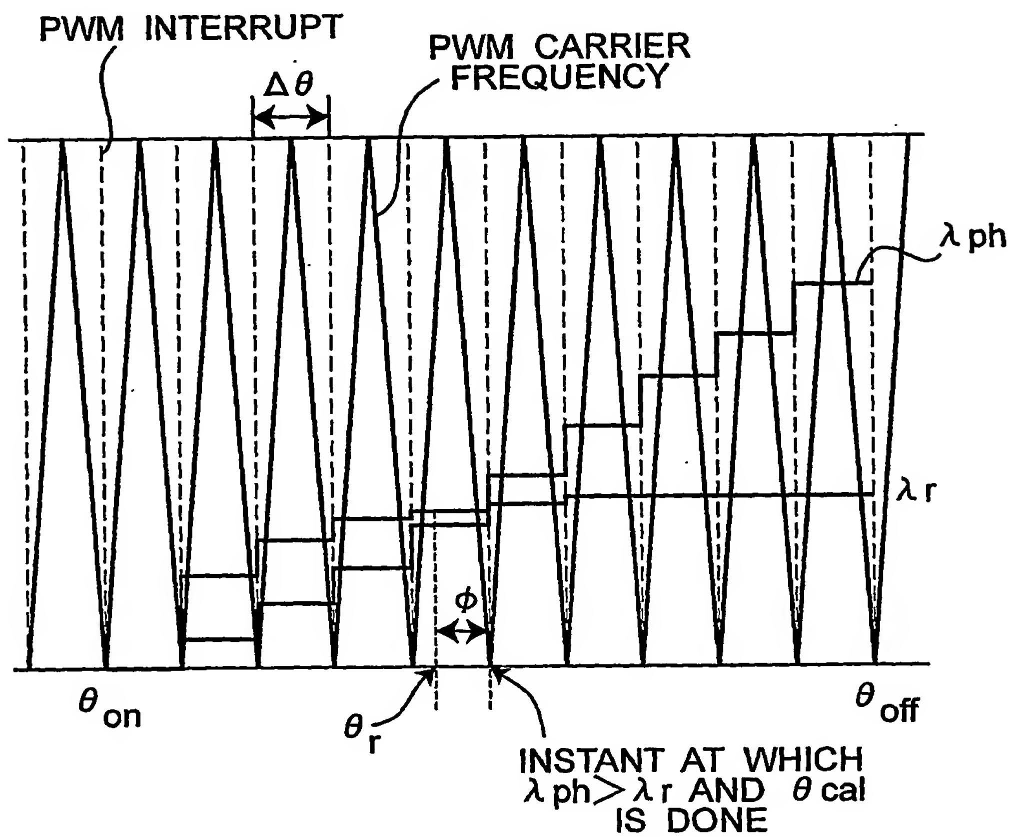

Lmax
Lmin
Lmax
Lmin
Lmax
PHASE INDUCTANCE
PHASE CURRENT
θ_1
θ_0
t_0
θ_2
ROTOR POSITION

Fig.8


PWM INTERRUPT
PWM CARRIER FREQUENCY
Δθ
λ ph
λ r
Φ
θ on
θ r
θ off
INSTANT AT WHICH λ ph > λ r AND θ cal IS DONE

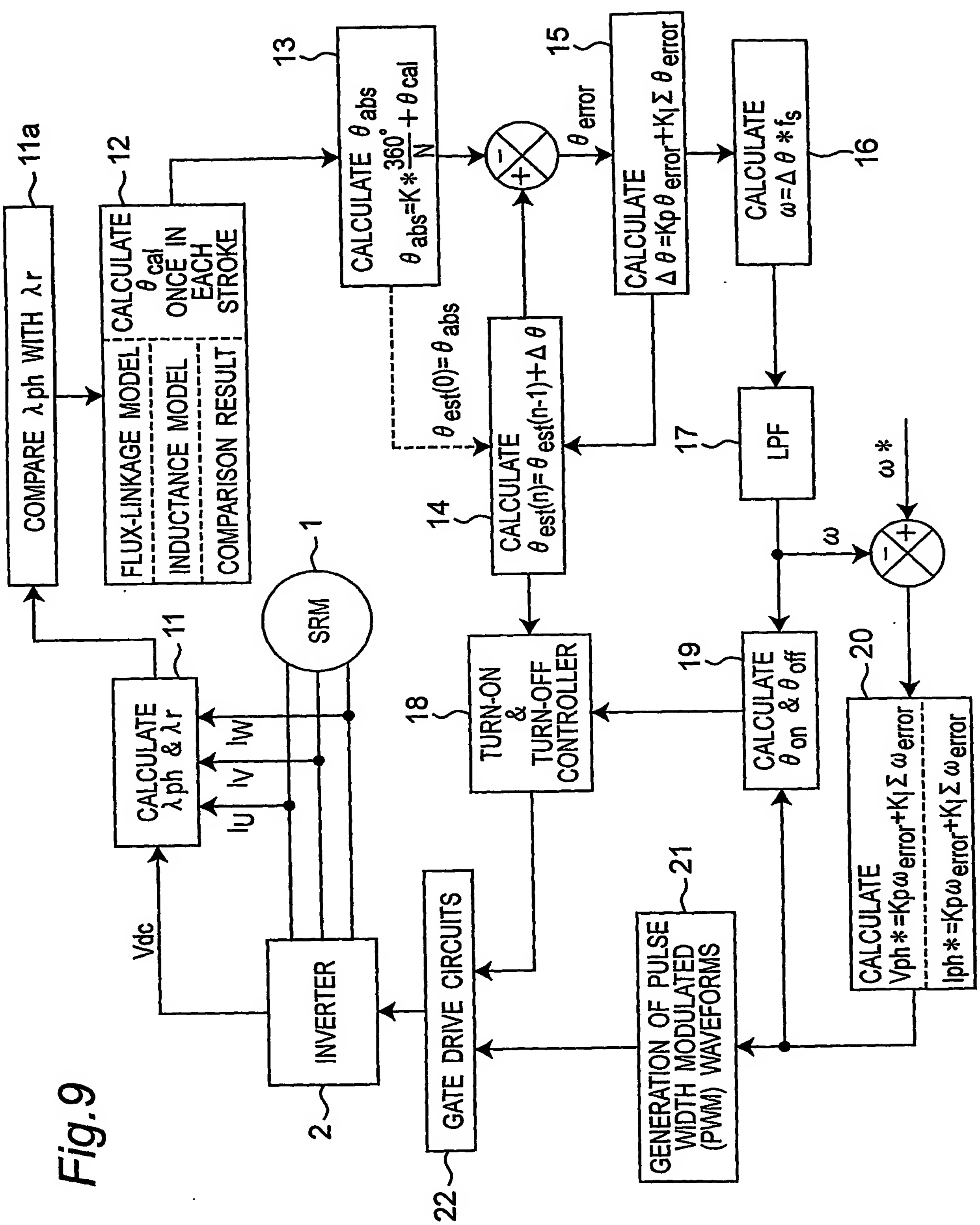
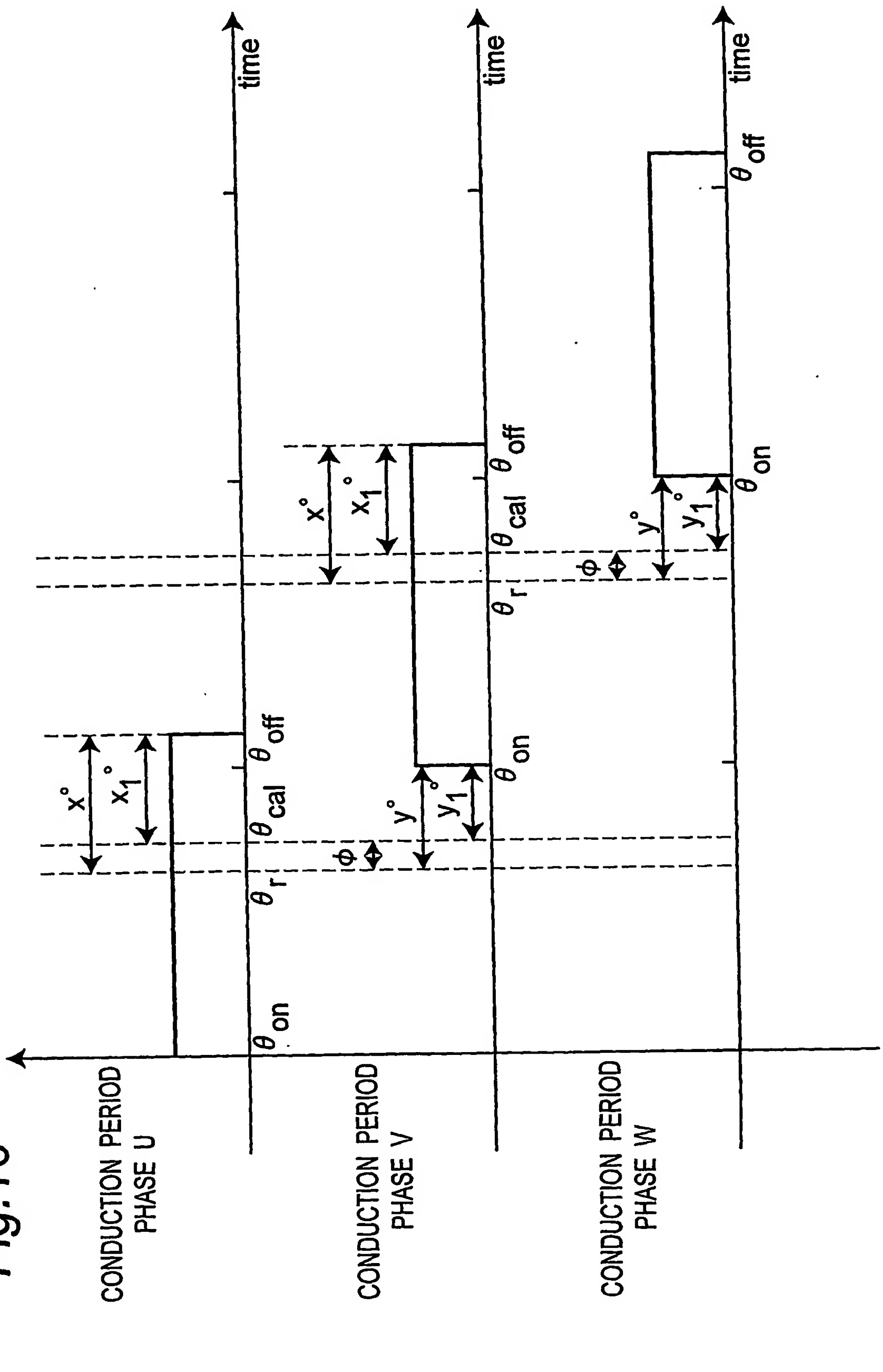

COMPARE λph WITH λr
11a
FLUX-LINKAGE MODEL
INDUCTANCE MODEL
COMPARISON RESULT
CALCULATE θcal ONCE IN EACH STROKE
12
CALCULATE θabs
θabs=K*360°/N+θcal
13
θerror
15
CALCULATE Δθ=Kpθerror+KIΣθerror
CALCULATE ω=Δθ*fs
16
θest(0)=θabs
CALCULATE θest(n)=θest(n-1)+Δθ
14
LPF
17
ω*
ω
1
SRM
11
CALCULATE λph & λr
IU
IV
IW
Vdc
18
TURN-ON & TURN-OFF CONTROLLER
19
CALCULATE θon & θoff
20
CALCULATE Vph*=Kpωerror+KIΣωerror
Iph*=Kpωerror+KIΣωerror
INVERTER
2
GATE DRIVE CIRCUITS
22
21
GENERATION OF PULSE WIDTH MODULATED (PWM) WAVEFORMS

Fig.9

Fig.10


CONDUCTION PERIOD
PHASE U
CONDUCTION PERIOD
PHASE V
CONDUCTION PERIOD
PHASE W
time
time
time
θ_{on}
θ_r
θ_{cal}
θ_{off}
$x°$
$x_1°$
$y°$
$y_1°$
ϕ

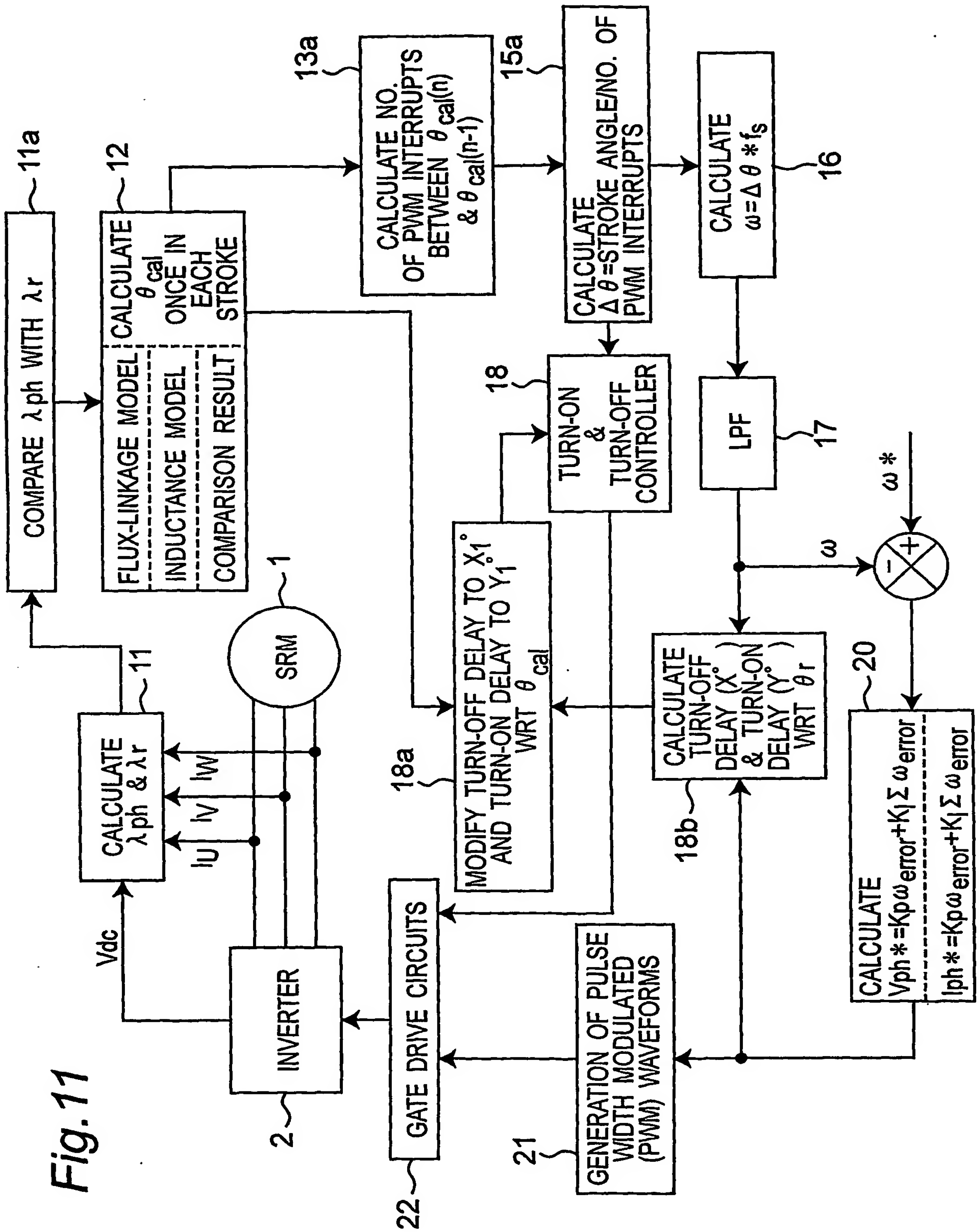

COMPARE λph WITH λr
11a
FLUX-LINKAGE MODEL
INDUCTANCE MODEL
COMPARISON RESULT
CALCULATE θcal ONCE IN EACH STROKE
12
CALCULATE NO. OF PWM INTERRUPTS BETWEEN θcal(n) & θcal(n-1)
13a
CALCULATE Δθ=STROKE ANGLE/NO. OF PWM INTERRUPTS
15a
CALCULATE ω=Δθ*fs
16
LPF
17
ω*
ω
+
-
TURN-ON & TURN-OFF CONTROLLER
18
MODIFY TURN-OFF DELAY TO X°1 AND TURN-ON DELAY TO Y°1 WRT θcal
18a
CALCULATE TURN-OFF DELAY (X°) & TURN-ON DELAY (Y°) WRT θr
18b
CALCULATE Vph*=Kpωerror+KIΣωerror
Iph*=Kpωerror+KIΣωerror
20
SRM
1
CALCULATE λph & λr
11
IU
IV
IW
Vdc
INVERTER
2
GATE DRIVE CIRCUITS
22
GENERATION OF PULSE WIDTH MODULATED (PWM) WAVEFORMS
21

Fig.11

Fig.12A

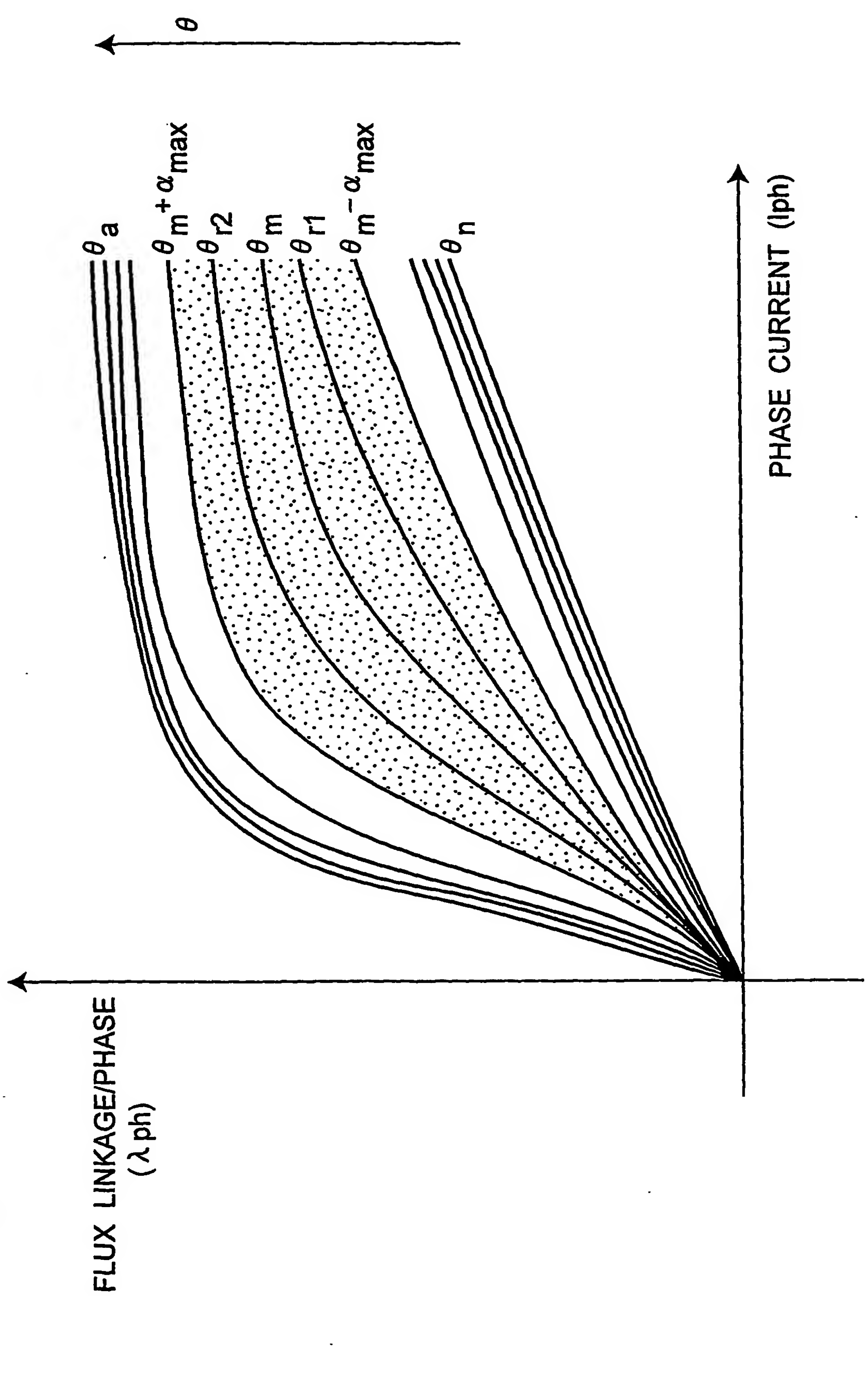

θ
θa
θm+αmax
θr2
θm
θr1
θm−αmax
θn
PHASE CURRENT (Iph)
FLUX LINKAGE/PHASE
(λph)

Fig.12B

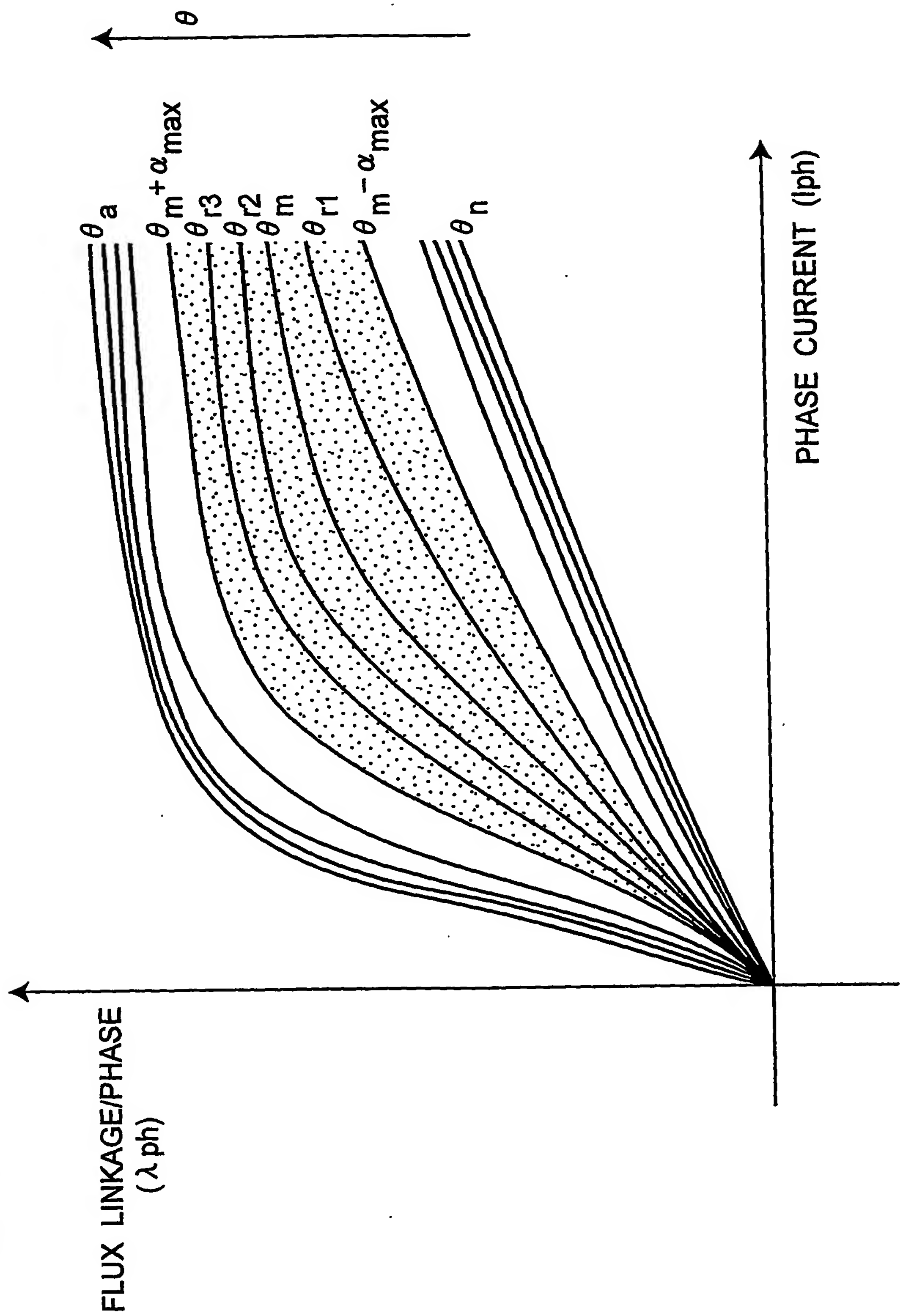

θ
θ_a
$\theta_m+\alpha_{max}$
θ_{r3}
θ_{r2}
θ_m
θ_{r1}
$\theta_m-\alpha_{max}$
θ_n
PHASE CURRENT (Iph)
FLUX LINKAGE/PHASE
(λph)

Fig.13

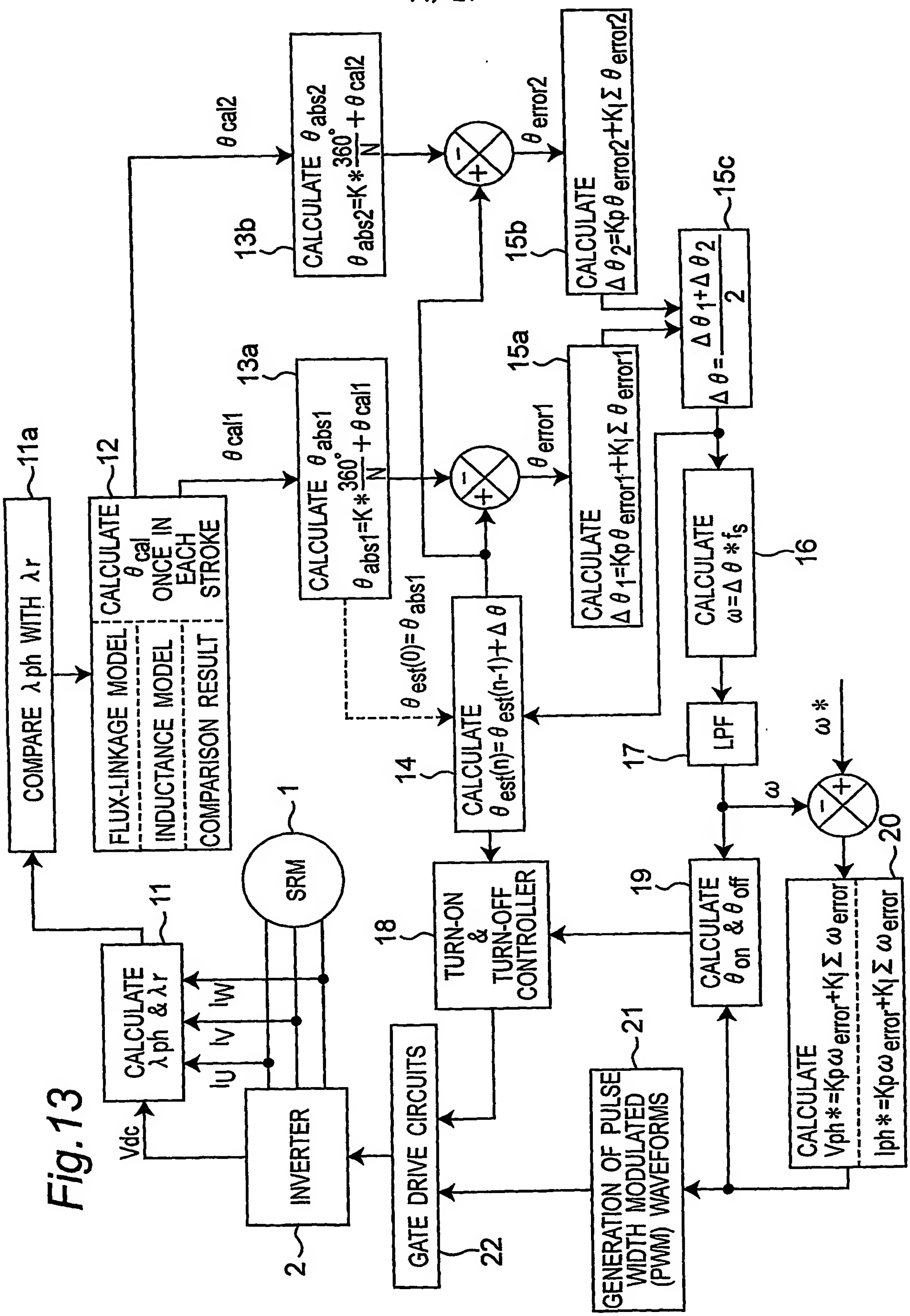

COMPARE λph WITH λr
11a
FLUX-LINKAGE MODEL
INDUCTANCE MODEL
COMPARISON RESULT
CALCULATE θcal ONCE IN EACH STROKE
12
θcal1
θcal2
CALCULATE θabs1
θabs1=K*360°/N+θcal1
13a
CALCULATE θabs2
θabs2=K*360°/N+θcal2
13b
θerror1
θerror2
CALCULATE
Δθ1=Kpθerror1+KIΣθerror1
15a
CALCULATE
Δθ2=Kpθerror2+KIΣθerror2
15b
Δθ=(Δθ1+Δθ2)/2
15c
θest(0)=θabs1
CALCULATE
θest(n)=θest(n-1)+Δθ
14
CALCULATE
ω=Δθ*fs
16
LPF
17
ω
ω*
20
CALCULATE
Vph*=Kpωerror+KIΣωerror
Iph*=Kpωerror+KIΣωerror
CALCULATE θon & θoff
19
TURN-ON & TURN-OFF CONTROLLER
18
SRM
1
CALCULATE λph & λr
11
IU
IV
IW
Vdc
INVERTER
2
GATE DRIVE CIRCUITS
22
GENERATION OF PULSE WIDTH MODULATED (PWM) WAVEFORMS
21

Fig.14

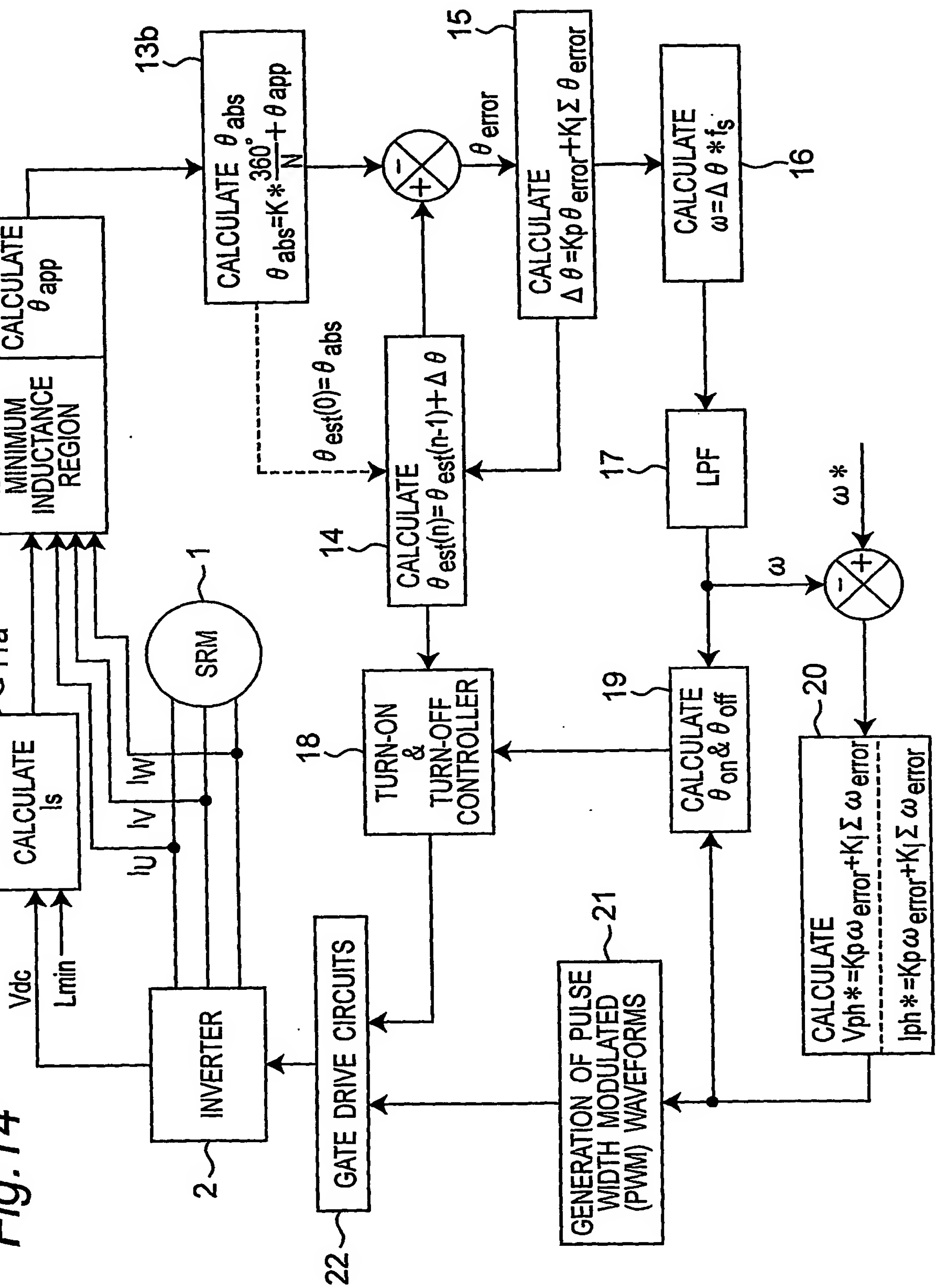

CALCULATE Is
IDENTIFY MINIMUM INDUCTANCE REGION
CALCULATE θapp
CALCULATE θabs
θabs=K*360°/N+θapp
θerror
CALCULATE Δθ=Kpθerror+KIΣθerror
CALCULATE ω=Δθ*fs
θest(0)=θabs
CALCULATE θest(n)=θest(n-1)+Δθ
LPF
ω
ω*
SRM
Iu
Iv
Iw
Vdc
Lmin
INVERTER
TURN-ON & TURN-OFF CONTROLLER
CALCULATE θon & θoff
GATE DRIVE CIRCUITS
GENERATION OF PULSE WIDTH MODULATED (PWM) WAVEFORMS
CALCULATE Vph*=Kpωerror+KIΣωerror
Iph*=Kpωerror+KIΣωerror
1
2
11a
12a
13b
14
15
16
17
18
19
20
21
22

Fig.15

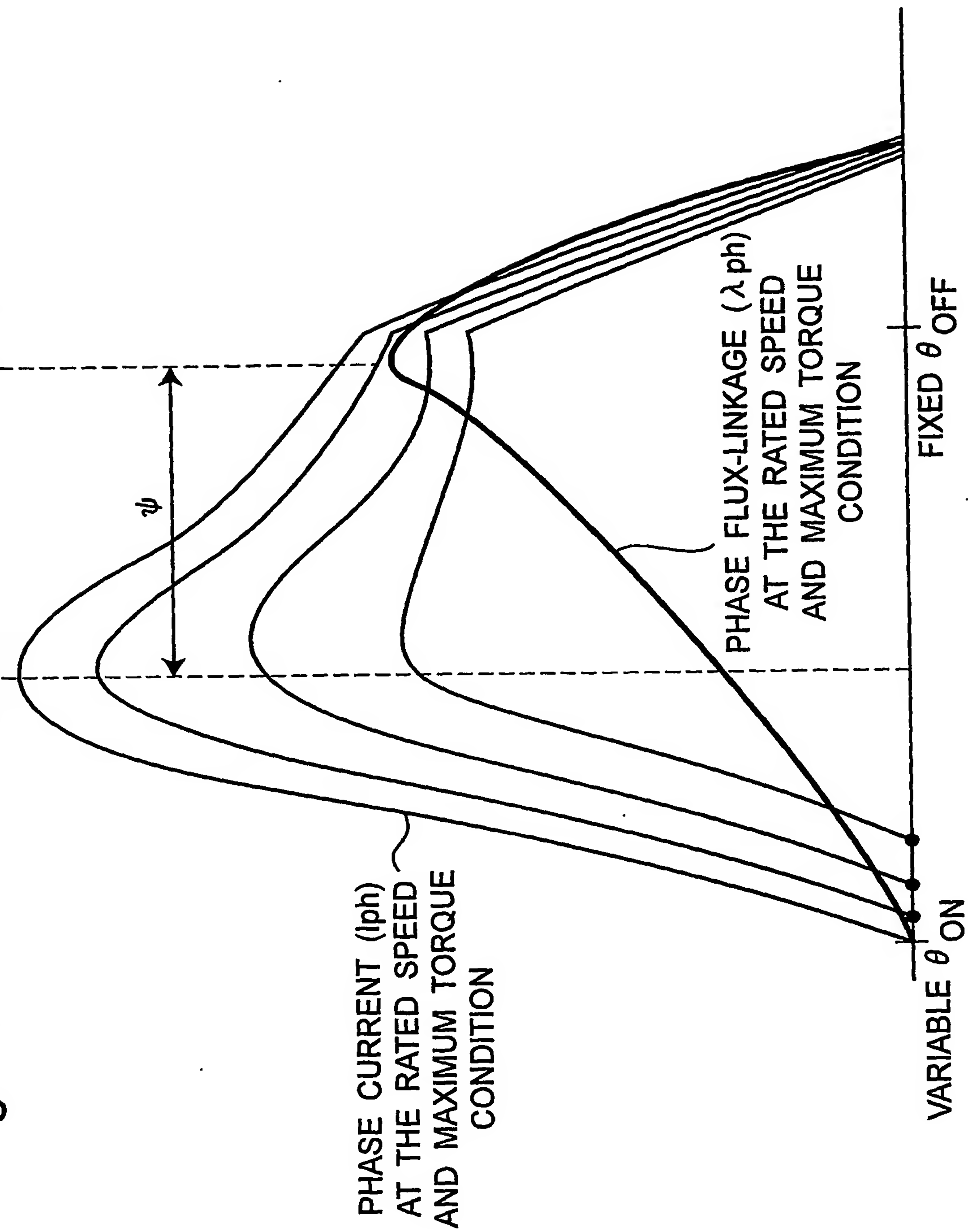

Iph(peak)
λ ph(peak)
ψ
PHASE CURRENT (Iph)
AT THE RATED SPEED
AND MAXIMUM TORQUE
CONDITION
PHASE FLUX-LINKAGE (λ ph)
AT THE RATED SPEED
AND MAXIMUM TORQUE
CONDITION
VARIABLE θ ON
FIXED θ OFF

Fig.16

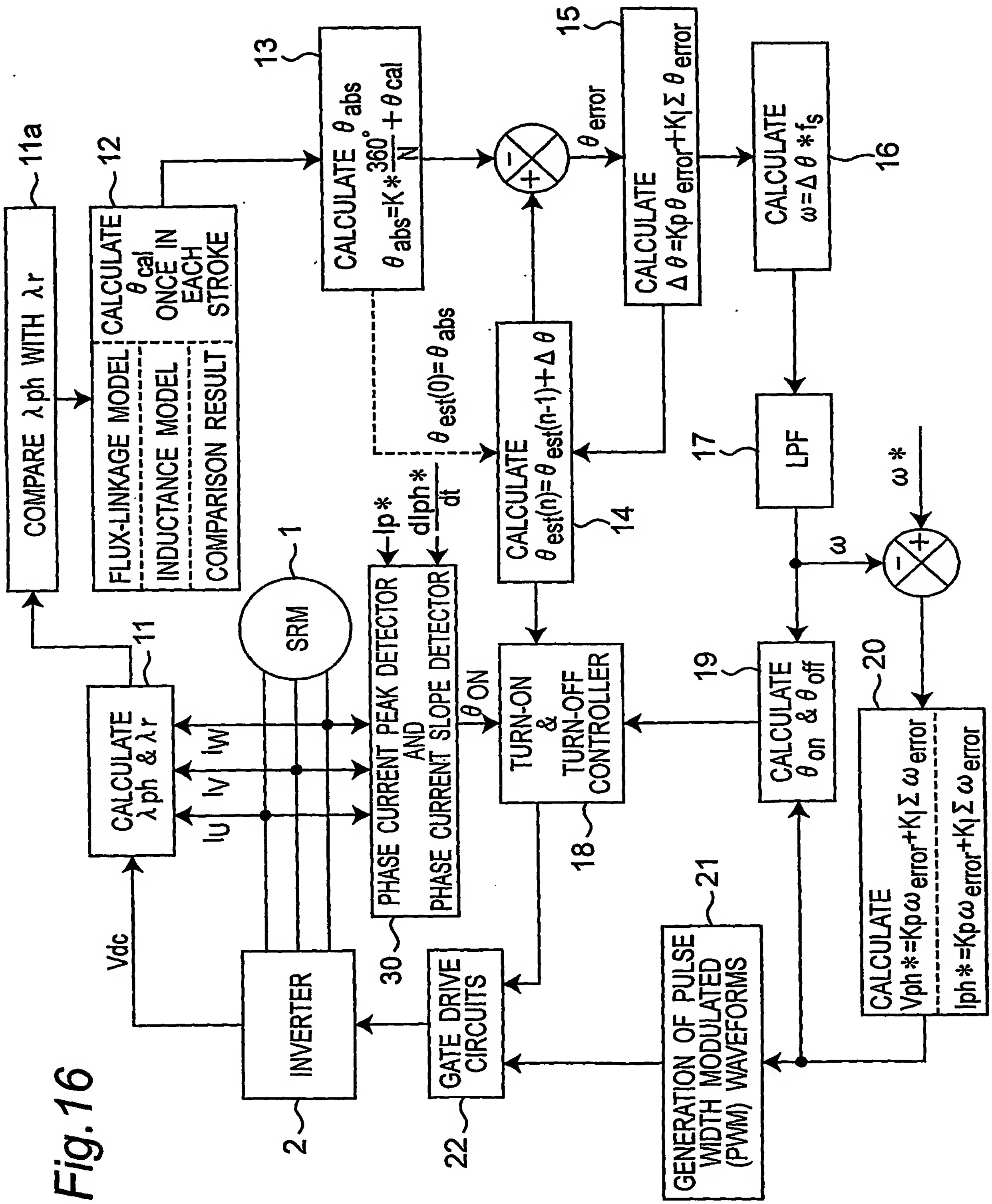

COMPARE λph WITH λr
11a
FLUX-LINKAGE MODEL
INDUCTANCE MODEL
COMPARISON RESULT
CALCULATE θcal ONCE IN EACH STROKE
12
CALCULATE θabs
θabs=K*360°/N+θcal
13
θerror
15
CALCULATE Δθ=Kpθerror+KIΣθerror
CALCULATE ω=Δθ*fs
16
θest(0)=θabs
CALCULATE θest(n)=θest(n-1)+Δθ
14
Ip*
dIph*/dt
LPF
17
ω*
ω
SRM
1
CALCULATE λph & λr
11
IU
IV
IW
PHASE CURRENT PEAK DETECTOR AND PHASE CURRENT SLOPE DETECTOR
30
θON
TURN-ON & TURN-OFF CONTROLLER
18
CALCULATE θon & θoff
19
CALCULATE Vph*=Kpωerror+KIΣωerror
Iph*=Kpωerror+KIΣωerror
20
Vdc
INVERTER
2
GATE DRIVE CIRCUITS
22
GENERATION OF PULSE WIDTH MODULATED (PWM) WAVEFORMS
21

Fig. 17A

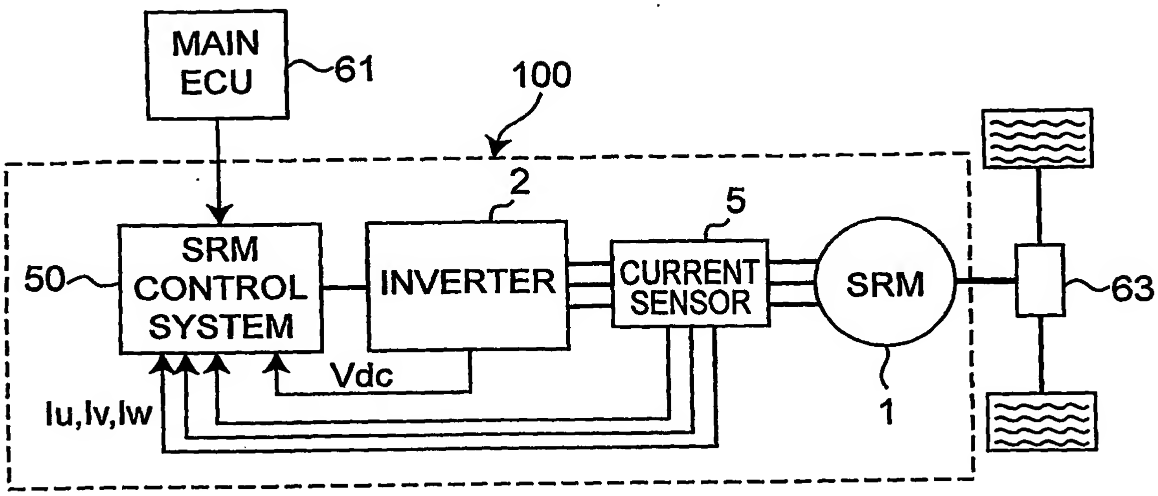


Fig. 17B

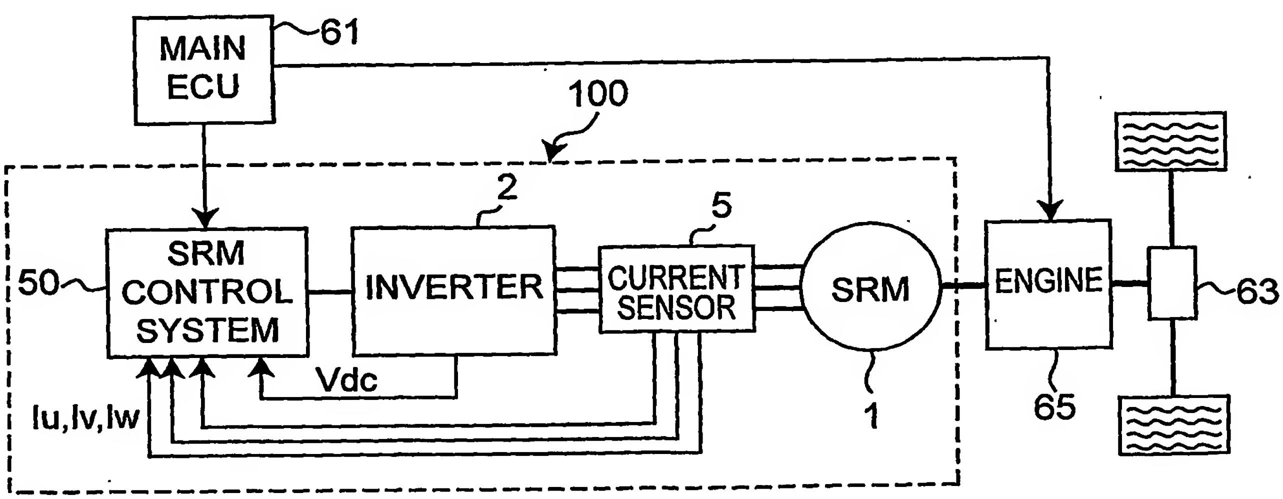


Fig.17C

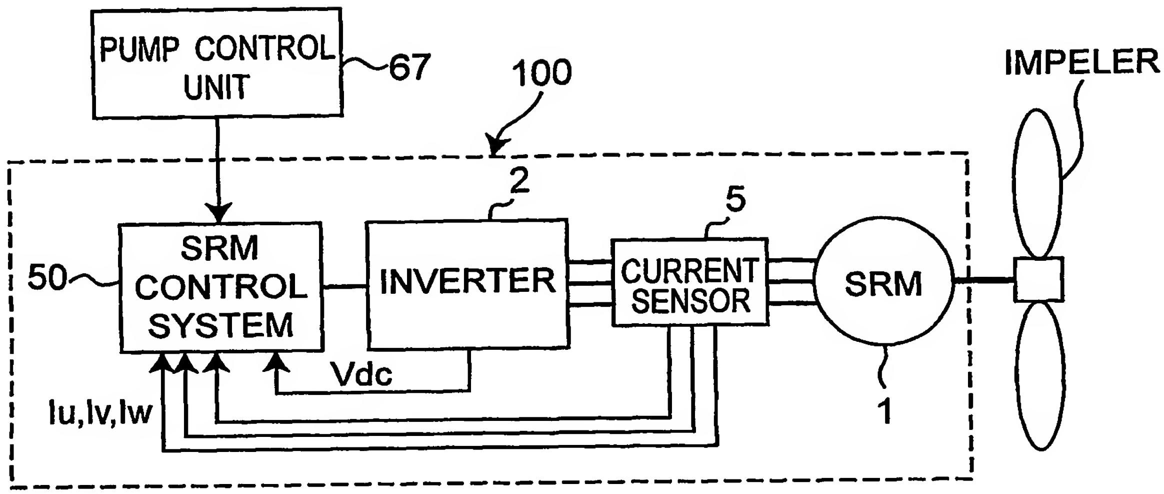


Fig.17D

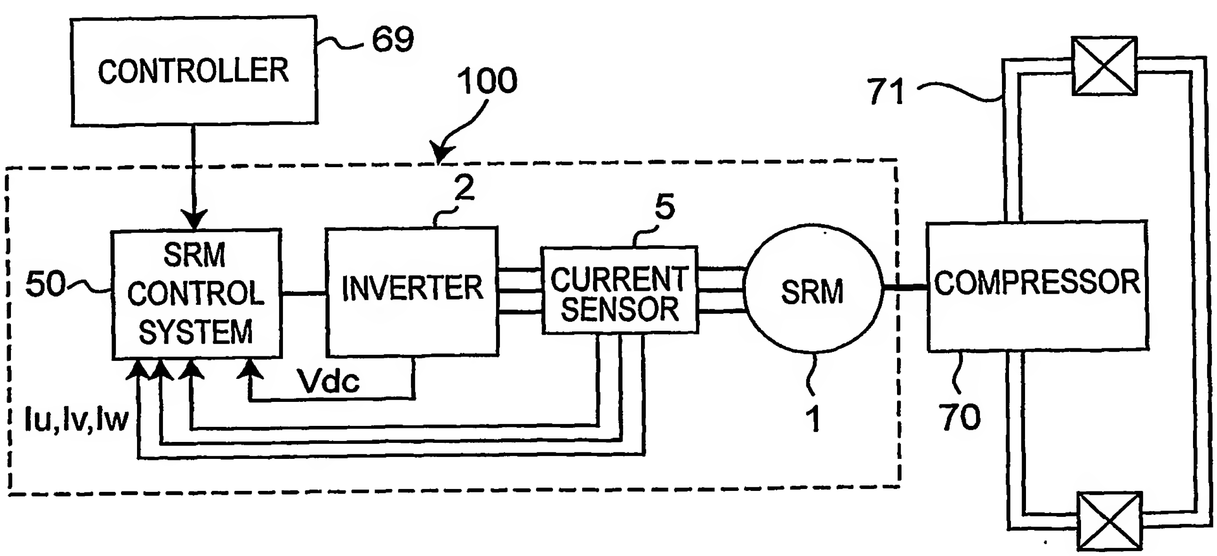


Fig.17E

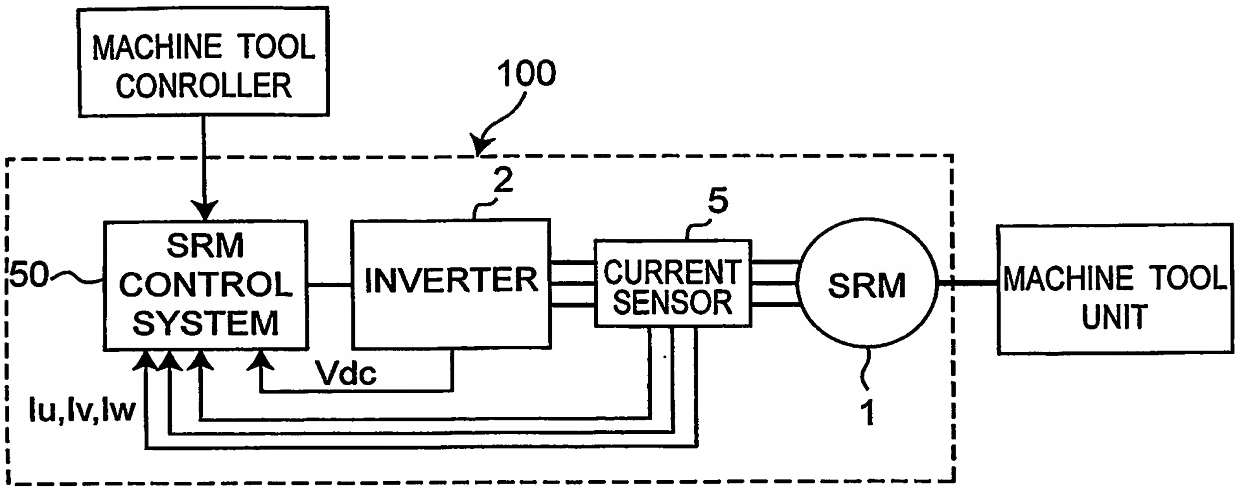


Fig.17F

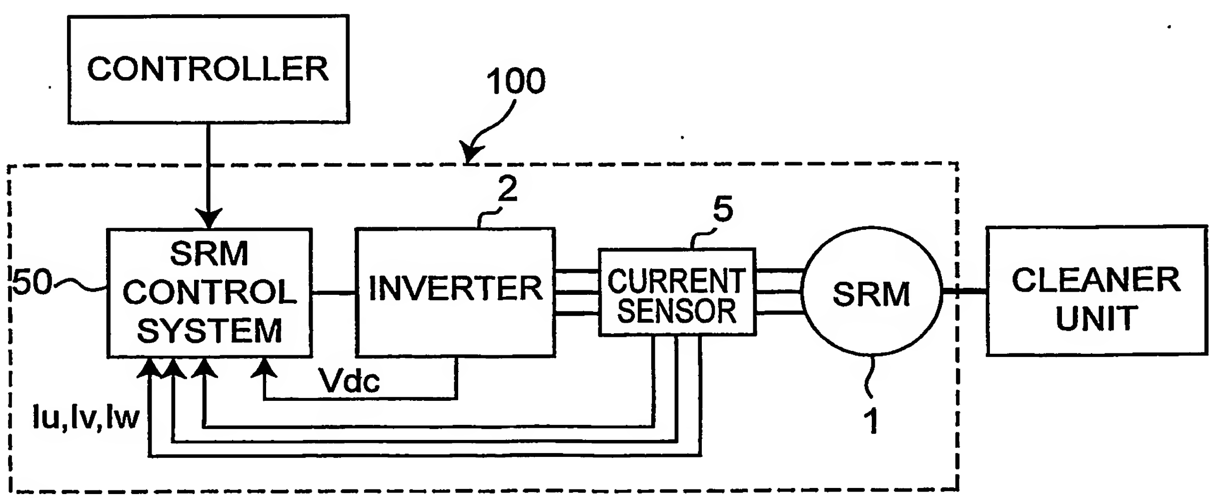
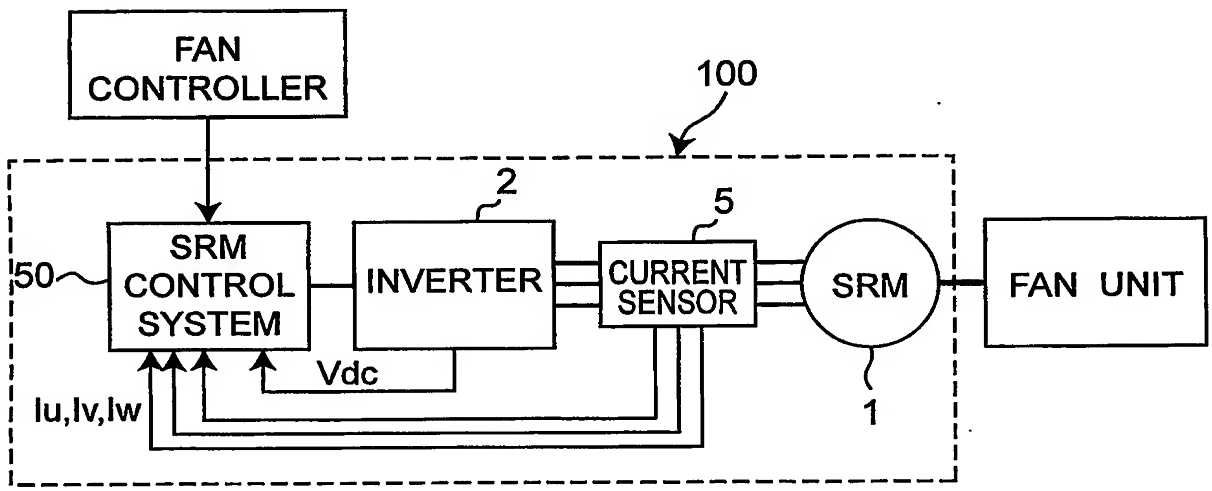


Fig.17G


FAN CONTROLLER
100
2
5
50
SRM CONTROL SYSTEM
INVERTER
CURRENT SENSOR
SRM
FAN UNIT
Vdc
Iu,Iv,Iw
1

INTERNATIONAL SEARCH REPORT

PCT/JP 02/12412

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H02P7/05

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H02P

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	FAHIMI B ET AL: "REVIEW OF SENSORLESS CONTROL METHODS IN SWITCHED RELUCTANCE MOTOR" , INDUSTRY APPLICATIONS CONFERENCE, 2000. CONFERENCE RECORD OF THE 2000 IEEE. VOL. 3 OF 5, PAGE(S) 1850-1857 XP010521364 ISBN: 0-7803-6584-4 page 1851, left-hand column, line 26 -page 1856, right-hand column, line 26 ---	1-32
X	EP 1 225 686 A (DELPHI TECH INC) 24 July 2002 (2002-07-24) page 2, line 26 -page 6, line 17; figures 1-6 ---	1-32
	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 April 2003	17/04/2003

Name and mailing address of the ISA	Authorized officer
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SURESH G ET AL: "Inductance based position encoding for sensorless SRM drives" , POWER ELECTRONICS SPECIALISTS CONFERENCE, 1999. PESC 99. 30TH ANNUAL IEEE CHARLESTON, SC, USA 27 JUNE-1 JULY 1999, PISCATAWAY, NJ, USA,IEEE, US, PAGE(S) 832-837 XP010346760 ISBN: 0-7803-5421-4 cited in the application ---	
A	SAHA S ET AL: "Developing a sensorless approach for switched reluctance motors from a new analytical model" , INDUSTRY APPLICATIONS CONFERENCE, 1999. THIRTY-FOURTH IAS ANNUAL MEETING. CONFERENCE RECORD OF THE 1999 IEEE PHOENIX, AZ, USA 3-7 OCT. 1999, PISCATAWAY, NJ, USA,IEEE, US, PAGE(S) 525-532 XP010355230 ISBN: 0-7803-5589-X cited in the application -----	

1

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Patent document cited in search report		Publication date	Patent family member(s)		Publication date
EP 1225686	A	24-07-2002	US	2002125851 A1	12-09-2002
			EP	1225686 A2	24-07-2002